SERDP REPORT

Infrastructure Damage/Fragility Models and Data Quality Issues Associated with Department of Defense Climate Vulnerability and Impact Assessment

JANUARY 2015

SERDP Office
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Approved for Public Release Distribution Statement A

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **26 JAN 2015**	2. REPORT TYPE	3. DATES COVERED **00-00-2015 to 00-00-2015**

4. TITLE AND SUBTITLE **Infrastructure Damage/Fragility Models and Data Quality Issues Associated with Department of Defense Climate Vulnerability and Impact Assessment**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Strategic Environmental Research and Development Program (SERDP),Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**117**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Infrastructure Damage/Fragility Models and Data Quality Issues Associated with Department of Defense Climate Vulnerability and Impact Assessment

ICF International

1/26/2015

Report authored by ICF International under subcontract to and with project management by HydroGeoLogic, Inc.

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List of Acronyms

ADCIRC	ADvanced CIRCulation Model
CONUS	Contiguous US
CO-OPS	Center for Operational Oceanographic Products and Services
CSDGM	Content Standard for Digital Geospatial Metadata
CSVR	Content-to-structure value ratio
DEM	Digital Elevation Model
DISDI	Defense Installations Spatial Data Infrastructure
DoD	Department of Defense
FACCode	Facility analysis category code
FEMA	Federal Emergency Management Agency
FGDC	Federal Geographic Data Committee
FGDC	Federal Geographic Data Committee
FIA	Flood Insurance Administration
FIMA	Federal Insurance Mitigation Administration
FLEMOps, FLEMOcs	Flood Loss Estimation MOdel
FOCO	For Official Use Only
FPHLP	Florida Public Hurricane Loss Projection model
GIS	Geographic information system
GLOBE	Global Land One-Kilometer Base Elevation Project
GPS	Global Positioning System
GTOPO30	Global 30 Arc-Second Elevation
HAZUS	Hazards U.S.
HAZUS-MH	Hazards U.S. - Multi-hazard
HEC-FDA	Hydrologic Engineering Center's Flood Damage Reduction Analysis
HIFLD	Homeland Infrastructure Foundation-Level Data
HIS-SSM	Damage and Victims Module
HSIP	Homeland Security Infrastructure Program
ICICLE	ISER Comprehensive Infrastructure Climate Lifecycle Estimator
IfSAR	Interferometry Synthetic Aperture Radar
iNFADS	Internet Naval Facilities Assets Data Store
ISER	Infrastructure Security and Energy Restoration
ISO	International Organization for Standardization
JALBTCX	Joint Airborne Lidar Bathymetry Technical Center of Expertise
JRC Model	Joint Research Centre Model
NAD83	North American Datum 83
NAVD88	North American Vertical Datum of 1988
NED	National Elevation Dataset
NFIP	National Flood Insurance Program
NGA	National Geographic-Spatial Intelligence Agency
NGDC	National Geophysical Data Center
NGS	National Geodetic Survey

NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NSDI	National Spatial Data Infrastructure
NSRS	National Spatial Reference System
NWI	National Wetlands Inventory
NWLON	National Water Level Observation Network
PI	Principal investigator
PSMSL	Permanent Service for Mean Sea Level
RAM	Rhine Atlas Damage Model
RMSE	Root-mean-square error
RPA	Real Property Asset
RPAD	Real Property Asset Database
RPCS	Real Property Classification Scheme
RPIM	Real Property Information Model
RTK	Real Time Kinematic
SERDP	Strategic Environmental Research and Development Program
SONAR	Sound and Navigation Ranging
SRTM	Shuttle Radar Topography Mission
STWAVE	Steady-State Spectral Wave
TIN	Triangular Irregular Network
UK	United Kingdom
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WAM	WAve prediction Model
WGS 84	World Geodetic System 84

Acknowledgements

This report was supported by a contract from the Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP). We thank the SERDP program manager, John Hall, for his support and insight. We also thank Elsa "Becky" Patton for useful context for this work and introduction to DoD staff for interviews, and Glen DeWillie of HydroGeoLogic, Inc., for his valuable technical review of the paper. We appreciate the technical review and contract management work of Sam Figuli of HydroGeoLogic, Inc. and contract management guidance from Craig Schultz of ICF International. Miyuki Hino of ICF International provided timely and attentive copy editing.

A number of experts gave us their valuable time by agreeing to be interviewed to inform the findings of this report. Interviewees included SERDP study Principal Investigators, representatives of the military Services, damage and impact model developers, and other experts identified by SERDP or through the interviewees. The interviewees included: Eric Berman, David Kreibel, Angela Schedel, Kelly Burks-Copes, Martin Schultz, Marianne Petty, Jose Rullan-Rodriguez, Michael Case, John Marra, Curt Storlazzi, Jeffrey Donnelly, Richard Moss, Joseph Donoghue, Steve Kish, Jim Elsner, Robert Evans, David LaBranche, Justin LaRose, Adam Parris, Chris Weaver, Shawn Lewers, and Robin O'Connell.

Note that the views in this report are the authors' alone, and do not necessarily reflect the views of the experts that were interviewed.

Executive Summary

This report provides input to the U.S. Department of Defense's (DoD) Strategic Environmental Research and Development Program's (SERDP) efforts to support climate vulnerability and impact assessments of infrastructure assets located at military installations. It considers the availability, quality, and usefulness of two distinct types of information to support assessments: (1) damage and fragility information, and (2) topographic, bathymetric, and asset data. It was informed in part by interviews with SERDP-funded research teams and a range of relevant experts from across the Services and academia.

Climate change vulnerability and impact assessments can be undertaken at different levels, or scales, within DoD, depending upon the decisions to be informed and the decision maker's tolerance for risk or uncertainty. The three scales that are the focus of this report are: (1) Service-wide assessment, (2) installation-level assessment, and (3) detailed, asset-level assessment. At the larger scales of this spectrum of assessment types, DoD planners can use assessments to identify and prioritize vulnerabilities and optimize resource allocation across or within Services or installations; at finer scales, DoD planners can benefit from detailed assessments for identifying specific infrastructure vulnerabilities, associated risks to missions, and asset-specific investments that may mitigate risks.

Damage and Fragility Information

Damage and fragility information can provide DoD planners with valuable insight into the 'response' of specific infrastructure to different climate hazard loads. This information can be derived using expert judgment, empirical methods, model-based analyses, and hybrids of the aforementioned methods. Damage and fragility information is typically integrated into impact models in the form of functions or curves to assess economic loss and/or physical damages to assets given different magnitudes of hazard loads. For the sake of clarity in this report, we distinguish fragility curves from damage functions as follows: fragility curves provide a probability of an asset being in a damaged state given a load on the asset; damage functions give the magnitude of damage (e.g., percent) to an asset as a function of the load on the asset. Note the distinction: one is a probability and the other is a level of damage.

Damages are represented in terms of physical damages (e.g., damage states), or percent damage to structures, which may be translated into economic losses associated with the value of the assets. Damage states represent the varying degrees of damage from minor to extreme. Damage states can include qualitative and quantitative descriptions regarding the physical damage or functionality of the asset, an important factor for identifying whether mission operations are at risk. Climate-related hazards may include riverine and coastal floods, wind and snow storms, temperature extremes, drought, fire, and others. The associated hazard loads can be represented as quantitative estimates of the physical forces to which an asset is subjected. For example, a flood hazard load may be represented by a certain water depth or water depth and duration; a wind hazard load may be defined as a certain wind speed for a given duration, or a wind pressure on a given structure.

Damage and fragility curves are often integrated into impact models whose primary purposes are to estimate damages and losses to inform planning, stimulate efforts to reduce the risks, evaluate potential hazard mitigation investments, and help in preparing for emergency preparedness, response, and recovery. At detailed assessment levels, fragility information can provide a probabilistic view of whether

a storm surge, flood, or high wind load could result in the loss of functionality of a particular mission-critical asset. At coarse assessment levels, generalized damage information (e.g., use of a 'representative' building for a particular asset class) may be applied to evaluate the total potential economic losses (e.g., building content replacement values) resulting from a flood that impacts a large geographic area. When embedded within impact models, these dose-response relationships can be used to test alternative scenarios to inform DoD investments (e.g., "hardening" vulnerable infrastructure) that may mitigate potential impacts on missions.

Summary of Findings

Our review of 13 impact models, several studies and other literature, and 10 expert interviews, indicates that the inputs required to inform the functional relationships between asset response and hazard loads are only available for some locations, assets, hazards, and damage metrics. The corresponding gaps could be a limiting factor for the application of these models at different assessment levels and in a range of settings. Fragility and damage information that is developed for a specific asset, location, and hazard load is not typically representative of that general type of asset at other locations. The reverse is also true: although highly aggregate damage or fragility information regarding an asset class response to a hazard load may be applied to represent the response of a general class of structures (e.g., residential, one story buildings) for large geographic areas, this generalized information requires calibration to be applied to an individual structure, in a specific geographic setting.

For most models, asset coverage is limited, and for all models, some key military assets are not covered: e.g., training facilities, armories, supply facilities (e.g., liquid storage, cold storage), and waterfront infrastructure (e.g., piers). In general, 'high potential loss' facilities (e.g., nuclear power plants, certain military and industrial depot-type facilities, dams) require treatment on an individual basis by users who have sufficient expertise to evaluate damage to such facilities. The Hazards U.S. (HAZUS) flood model is a notable exception, in that it covers a significantly greater breadth of asset types than any other model. According to many of the experts interviewed for this study, the HAZUS damage information provides a useful starting point for developing tailored damage or fragility curves for specific assets, in specific locations. DoD has made investments in the development of new methodologies that have resulted in the development of detailed damage and fragility information to better understand the vulnerability of specific mission critical assets at some military installations (e.g., Burks-Copes et al., 2014; Chadwick, 2013). Note that the potential exists to incorporate the detailed damage and fragility information (for wind and flood-related loads) from those studies back into impact models like HAZUS. It would be valuable to expand the set of detailed damage and fragility curves to cover a wider swath of high priority DOD specific asset types.

For most impact models, much of the existing damage and fragility information incorporates a damage metric representative of direct economic loss as a result of infrastructure damage. A damage metric that is arguably more important for some DoD purposes, but that is generally absent from impact models, is one that captures infrastructure functionality to help assess mission jeopardy. Indirect, cascading failures, due to system interdependencies, are also often absent. Finally, only two hazards were identified that are incorporated into the damage and fragility curves within the publically available, well known set of impact models that are suitable for usage across military installations: flood and wind.

Recommendations Regarding Damage and Fragility Information

Based on our analysis, we make the following recommendations to DOD:

New investments in damage and fragility information would benefit from a prioritization exercise of DoD vulnerability assessment needs cross-walked against the currently available damage and fragility information in order to identify the missing damage and fragility information that is most needed to support the range of assessment levels. As one moves from the Service-level screen to the detailed assessment level, the level of detail of the damage and fragility information should correspondingly increase. Prioritization will allow for some filtering of information requirements, which can cut down on cost and time requirements.

A systematic approach for monitoring and recording disaster losses and hazard events at military installations would provide DoD critical observations and inform future studies and decisions. Efforts to increase knowledge of the system response to climate hazards, including investments in weather, hydrologic monitoring, and impacts data, can provide critical information to decision makers given the uncertainty surrounding current impacts, and future climate variability and change. This information can be useful to developing more accurate damage and fragility functions for specific locations and assets.

Generalized fragility or damage curves should be developed for a core set of common mission critical assets for installations and Services. For more detailed analysis, tailored fragility or damage information could be developed for mission critical assets. For Service- or installation-level analysis, less detailed (highly aggregated) damage and fragility information may be adequate for identifying where there are significant vulnerabilities. For detailed vulnerability assessments, DoD should invest in highly detailed, asset-specific damage and fragility information for mission critical assets, to better determine mission vulnerability and to evaluate response options.

At the department-wide screening level, and for some Service-level screening assessments, the use of damage and fragility information may not be appropriate, and alternative approaches should be considered. Although coarse or highly aggregated damage information may be applied at large scales to provide an overall picture of loss, it will often result in significant inaccuracies at the scale of individual assets that can provide misleading results. Alternative screening methods—for example, a focus on exposure (e.g., overlaying hazard and asset information) rather than on sensitivity (as in the use of damage and fragility modeling)—can be a cost effective way to initially screen for vulnerability. An even less costly approach could be to rely heavily on expert knowledge to provide an initial indication of installations at risk now and in the future.

Service-level vulnerability assessments in areas facing similar hazards and with similar geographies, provide potentially good opportunities to use aggregate damage information (including from the HAZUS library). For example, a comparison of the relative vulnerability of coastal installation asset types to sea level rise and storm surge provides one such opportunity.

Despite limitations, the HAZUS flood and wind models currently provide the most comprehensive set of damage and fragility information for DoD purposes, and the application of this information is particularly appropriate for use in installation level assessments. At more detailed assessment levels,

HAZUS information can provide a useful starting point for development of more tailored damage information. The HAZUS flood model provides the best coverage of military assets of any of the reviewed models, though flood damage information for the following military assets is not available: training facilities, armories, supply facilities (e.g., liquid storage, cold storage), and waterfront infrastructure (e.g., pier). Depending upon the purpose, these may represent high value assets in terms of mission criticality or monetary value.

Data Quality Assessment

Impact and vulnerability assessments that are designed to inform decisions at any level of analysis, from Service-level screening to detailed assessment, often use topographic, bathymetric, and asset data. For these analyses to be reliable and defensible, the data must be of appropriate quality and accessible to DoD. This report provides an analysis of the data quality of topographic, bathymetric, and asset data relevant to military installations, especially coastal locations. Data quality is defined in this report as the attributes of the data that can affect their utility in impact or vulnerability assessment, such as the accuracy, resolution, reference datum, spatial and temporal extent and coverage, metadata, frequency of collection, and model-related error. We selected a sample of military installations that represents a broad geographic distribution across different geographies (e.g., Japan, Italy, east coast of United States, and west coast of United States) and multiple DoD Service branches to analyze potential difference in data quality. Although each assessment will differ in decision context, from our review, we identified findings and recommendations related to data quality for the levels of assessment outlined previously.

Summary of Findings

In this study, we found topographic data of high quality for sampled military installations in the continental United States. The topographic data sampled for military installations generally follow internationally recognized metadata standards. The vertical accuracy and horizontal resolution vary by collection method, with the sample of military installations indicating easily accessible Lidar-based topographic data for coastal US locations, primarily through the National Elevation Dataset (NED). For locations outside of the coterminous United States, readily available data tend to be found at a lower resolution, which may not be suitable for installation-level screening or detailed analyses. In those cases, additional data collection may be needed to support assessments where a high level of certainty is needed to support decision making. In some domestic and international locations, classified data may exist at higher resolutions, but assessment of these data was beyond the scope of this study.

Bathymetric data vary in quality for the installations sampled as part of this study. Our review of the metadata revealed that though these metadata are provided in internationally recognized formats, the horizontal and vertical resolutions are often not included, particularly for the older survey records. The sampled bathymetric data, especially those collected through the National Ocean Service Hydrographic Surveys, often report vertical and horizontal datums, though not in all instances. For installations within the United States, the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center provides the most continuous layer of high resolution bathymetric data. We found extensive coverage of multibeam sonar data, both in US coastal waters and globally, which is important for Service-wide screening assessments that require comparable data. In situations that have low tolerance for uncertainty (i.e., detailed assessments), collection of new bathymetric data may be

necessary to provide high-resolution data of known horizontal accuracy and an up-to-date understanding of the bathymetry.

The quality of asset data for the installations sampled varies widely. The DoD Real Property Asset Database (RPAD) is intended to include all DoD real property, such as buildings, linear structures (e.g., pipelines, fences, power lines), and land. However, it was difficult to confirm the extent to which installation assets are included without ground-truthing or cross-referencing with other data sources. Our review found that for the sampled installations, all assets are classified for a predominant use by the DoD Real Property Classification Scheme (an important step for considering applicability with HAZUS), and nearly all assets have a facility replacement value, which is critical for assessing economic damages from impacts. Other database fields important to impact or vulnerability analysis (i.e., construction material and functional capability), however, were incomplete or not informative. Data quality issues also exist for the Homeland Security Infrastructure Program (HSIP) Gold data from the Homeland Infrastructure Foundation-Level Data (HIFLD). In reviewing layers applicable to military installations, we found that no metadata exist for some HSIP Gold layers—at least these metadata are not supplied with the standard distribution—and there are obvious gaps in asset information. Although RPAD and HSIP Gold represent the best available standardized data, review of record quality and completeness is needed in application and interpretation to specific locations. These issues may improve over time with the continued use of RPAD upper-level data validation processes already in place.

Recommendations Regarding Data Quality

Data for reliable and defensible impact and vulnerability assessments, no matter the analytical level, must have metadata that adhere to accepted guidelines, the FGDC or ISO standards in particular. The ability to conduct certain analyses may be hindered by incomplete metadata. In addition, data used in analyses should be converted to consistent appropriate datums: NAVD88 and NAD83 for US installations.

The spatial coverage and continuity requirements of the data will be related to the specific decision and tolerance for uncertainty; Service-level analyses will likely tolerate the uncertainty introduced by interpolation of data to un-sampled regions or by combination of different datasets, whereas detailed assessments will likely require consistently collected and continuous original topographic or bathymetric data. The limitations in an installation-level analysis will depend on the degree of discontinuity or lack of coverage.

For topographic and bathymetric data analyzed in this review, continuous data are generally available to support an installation-level analysis across coastal US locations; however, due to the non-uniform Lidar vertical error, additional review of local error may be needed to confirm reported values. Non-coastal locations and international installation sites have data coverage, but usually not at a vertical accuracy sufficient to support installation-level assessments.

The vertical error of a dataset has a large influence on delineating inundation zones, especially in coastal areas with low topographic relief, as opposed to steep coastal relief. For Service-level screening, where comparability across global installations is needed, standard topographic data, such as

Global 30 Arc-Second Elevation (GTOPO30) or Shuttle Radar Topography Mission sources, may be appropriate. In areas of low relief, the uncertainty in impacts or vulnerability that rely on these data will be high, but may be sufficient for identifying priorities across a military Service.

The length of record for tidal stations is important for all levels of analysis and updates to local datums may be needed for detailed assessments at particular installations. In situations where tidal records are shorter than the recommended 40 years, the error introduced in interpolating from other stations will likely impact the ability to conduct a detailed assessment. Common techniques for dealing with shorter length of records should be sufficient for Service-level screening analysis, but the effect on installation-level screening analysis will vary. In situations where there is low tolerance for uncertainty (i.e., detailed assessments), datum values may need to be updated to reflect current conditions with more recent observations.

Frequency of collection or last update to records of topographic, bathymetric, and asset data varies at the locations sampled in this review. In many coastal locations, recent topographic and bathymetric data will be needed, especially for installation-level screening or detailed assessments. For asset data, the time since the last update to the building replacement value or facility physical quality will increase uncertainty. In addition, projecting impacts onto the current installation inventory over 100 years may introduce significant uncertainty due to the turnover in installation inventory, which can be as short as 20-30 years.

General Recommendations

In addition to the recommendations specific to damage and fragility information and data quality, several overarching recommendations emerged from our analysis:

The data and information needs of an impact or vulnerability assessment will depend on the decisions that will be addressed. Aligning the information needed to the type of decision being made can reduce costs and help produce actionable results. The desired degree of confidence that a decision is correct dictates desired data quality. Therefore, decision makers should consider their tolerance for risk or uncertainty to guide the determination of whether data of sufficient quality are accessible.

In general, analysts and decision makers should keep in mind that for any given analysis that is supporting a decision, the ability to inform that decision will be limited by uncertainty across all datasets and models. Combing high accuracy topographic data with low accuracy asset elevational data does not improve the value beyond the low accuracy data, for example. Finding consistency in data types within a particular analytical level will support efficient collection and use of data.

The time period of the decision to be informed may affect the requirements for data and information needs. For example, in an assessment looking out 100 years where the historical record suggests that over the last 100 years changes due to natural coastal dynamics was on the scale of many meters, sub-meter accuracy data will not reduce the uncertainty in the findings, even for a detailed assessment.

Aligning the appropriate level of analysis with information and data quality will require careful consideration by DoD decision makers and analysts, recognizing that new data, information, or tools

may be required. Because different decisions and risk tolerances require different types and characteristics of information, a single, simple statement is not possible on whether sufficient damage and fragility information or topographic, bathymetric, and asset data quality exists. Our analysis provides insights into key considerations in utilizing these data and information for impact and vulnerability assessment.

1.0 Introduction

1.1 Context and Scope of Study

The US Department of Defense (DoD) will need to adapt to climate change impacts across a range of activities and infrastructure (DoD, 2014). With many of DoD's military installations concentrated in coastal regions, impacts and vulnerability to sea level rise, storm surge, and high winds from strong storms are priority concerns (SERDP, 2013; NRC, 2011). The purpose of this review is to provide input for DoD's Strategic Environmental Research and Development Program's (SERDP) efforts to support climate change vulnerability and impact assessments that address hazards such as these to infrastructure at military installations.

This report is divided into two separate but related main sections. The first section focuses on infrastructure damage and fragility information that can be used to inform vulnerability and impact assessments. The second main section focuses on the quality of topographic, bathymetric, and asset data, where asset data includes real property, such as buildings, linear structures, and land. This report summarizes and synthesizes prior knowledge, including the experience and findings of SERDP-funded research projects that have used various models, tools, and data to evaluate installation-level, climate-related risks in coastal locations. A case study on the Hazards U.S. (HAZUS) model at the end of the report provides a focused discussion on the applicability of HAZUS and available data for impact and vulnerability assessment at a military installation.

Although this report is meant to be informative to anyone designing climate change impact or vulnerability assessments at military installations, it does not address specific approaches for designing such assessments. This study is focused on a particular set of information and models and does not provide review and analysis across all models relevant to impact or vulnerability assessments, for example hydrologic or storm surge models. In addition, this study addresses data quality with respect to topographic, bathymetric, and asset data, and only provides general information regarding other data types that may be relevant to assessments.

1.2 A Framework for Levels of Analysis

For DoD, climate change vulnerability and impact assessments can be used at different levels, or scales, to inform an array of decisions, including the allocation of resources to ensure that installation infrastructure is able to support DoD activities and ensure military readiness (SERDP, 2013). The level of analysis, or the degree of granularity that is required in an assessment depends on the nature of the decisions to be made, how critical the infrastructure under consideration is to military readiness or other considerations, what threshold of risk tolerance would require action, and the cost of the assessment compared to the cost of a response decision, including inaction (SERDP, 2013).

For example, if a military Service leader needs to make a decision across a Service about long-term funding priorities that will be resilient to current and future climate variability and change, the decision requires information on the vulnerability of each installation at the level that is comparable across installations. Additional or more detailed information beyond what is required for the decision will

generally waste resources. The decision maker's risk tolerance or acceptance of uncertainty in a decision will also inform the quality of data and models needed to support the analysis.

Although there is an understandable desire to investigate detailed potential impacts or vulnerabilities at every location in as much detail as possible, this is not an efficient way to approach the problem. In general, vulnerability assessments should progressively move from the higher levels to the lower levels, focusing in increasing detail on the systems and assets that are both most important and most vulnerable, as revealed in assessments at the preceding, higher level. This approach can better target resources where they are needed. Having said that, in some cases where decisions at lower levels are imminent and clearly subject to climate-related risks, or where high consequence impacts and vulnerabilities are known, it may be advisable to not await the results of assessments at the higher levels.

Here we propose five levels of analysis for understanding vulnerabilities and impacts to climate variability and change in military settings:

Department-wide Screening: similar to analysis previously conducted in advance of the 2010 Quadrennial Defense Review, potential impacts and vulnerabilities are described in general terms and not necessarily with respect to specific installations. This level is not explicitly addressed in this study.

Service-level Screening: identifies vulnerable installations; inter-installation comparison; utilizes readily available data; used to inform where additional assessments are needed and priority investment areas.

Installation-level Screening: within an installation; identifies priorities *within* an installation; determines vulnerable mission critical facilities and Services.

Detailed Assessment: within priority areas within an installation; quantifies specific asset-level vulnerabilities and potential impacts on mission critical facilities and Services; identifies key design factors that may need to be considered further or modified.

Engineering Design and Construction Planning: feasibility design and construction-level planning; could include the use of probability-based design, or robust fragility curves, to consider the probability of infrastructure failure for a given set of climate-related hazard loads on the infrastructure (or a sub-component); methods and tools for conducting this level of analysis are not explicitly addressed in this study; nevertheless, some of the considerations in the Detailed Assessment stage are relevant to this stage.

The selection of the vulnerability and impact assessment analysis level should be driven by the nature of the decisions being made, including the decisions' spatial (national versus regional versus individual installation) and temporal (long- versus short-term) dimensions. Not all adaptation decisions require detailed assessment. Service-level or Installation-level screening assessments can be conducted relatively rapidly (i.e., several weeks to months depending on exact purpose and scope) to identify and prioritize the infrastructure and operations across the Service or at installations that may be vulnerable. In some cases, the findings will warrant a more detailed assessment to identify specific impacts and inform the appropriate adaptation response. This study addresses damage and fragility information

requirements and data quality issues relevant to the middle three levels of assessment. One reason for this focus is that DoD has recently completed a Department-wide screening and therefore input from this report on that level of analysis would not be timely. In addition, comments on Engineering Design and Construction Planning considerations require a level of detail and analysis beyond the scope of this study. However, such an analysis could build on this report.

1.3 Methodology

In this review, we identified and used peer-reviewed literature, government reports, and public and controlled-access government databases, model manuals, and PhD theses, through a literature and internet search to provide background and data for analysis. Recent and on-going SERDP studies provided a starting point, especially RC-1700 (Donoghue et al., 2012), RC-1701 (Burks-Copes et al., 2014), RC-1702 (Evans et al., 2014), and RC-1703 (Chadwick, 2013). The SERDP studies, along with our previous experience, informed our initial perspectives on important aspects of data quality and damage information to consider in this study.

The authors conducted a series of interviews to complement the literature reviewed. Interviewees included SERDP study principal investigators (PIs), key individuals identified by SERDP, military Service representatives, developers of damage or impact models, and individuals identified as experts through an initial set of interviews totaling 24 individuals (see Appendix A for a list of persons interviewed). Seven additional experts were identified and we attempted to reach them, but were unable to contact them for interviews. The interviews were semi-structured, with a general set of questions designed to elicit knowledge and information from the experts on types of data and/or fragility and damage information used in impact or vulnerability assessments. The interviews concerning the use of damage and fragility information focused on identifying the models and tools the military is currently using, the value of these models to the military, and the gaps in current knowledge and application. For data experts, the interviews focused on the sources of these data, the quality of available data, data gaps, and strategies to address relevant gaps. From the general set of questions, additional questions were tailored to take advantage of the broad range of backgrounds and knowledge of the experts that were interviewed.

2.0 Review of Damage and Fragility Information for Use in Infrastructure Vulnerability and Impact Assessments

The purpose of this section is to review damage and fragility information that can be used for climate vulnerability and impact assessments of infrastructure on military installations. This section begins by introducing and defining the terminology specific to damage and fragility information, including its purpose, use, and limitations in supporting impact and vulnerability assessments. Next, this section describes the impact models included in the review and the criteria used to evaluate the models, before providing an in-depth review of the models categorized by hazard, with a focus on the applicability of damage and fragility information (i.e., coverage of hazard loads, assets, direct and indirect impacts, and model uncertainties) for military installations. A brief review is provided of studies that were identified that quantify infrastructure damages associated with landslides, temperature extremes, changes in temperature, rainfall and flooding, snow loads, permafrost, and freeze-thaw cycles. Finally, the review concludes with a set of recommendations regarding the use of damage and fragility information for military installations.

2.1 Introducing Damage and Fragility Information

Damage and fragility information is asset and context specific, and provides information on the potential for damage given exposure to a range of hazard loads (Davis and Skaggs, 1992; Schultz et al., 2010). This information can be derived using expert judgment, empirical methods, model-based analyses, and hybrids of the aforementioned methods (Schultz, 2010). Damage and fragility information is typically integrated into impact models in the form of functions or curves to assess economic loss and/or physical damages to assets given different magnitudes of hazard loads.

Fragility curves are not the same thing as damage functions, though they are sometimes used interchangeably. For example, fragility curves are sometimes called damage state curves (e.g., in the Hazards U.S. - Multi-hazard (HAZUS-MH) MR4 Technical Manual (FEMA, 2009)). For the sake of clarity in this report, we distinguish fragility curves from damage functions as follows: fragility curves provide a probability of an asset or system being in a damaged state given a load on the asset; damage functions give the magnitude of damage to an asset as a function of the load on the asset. Note the distinction: one is a probability and the other is a level of damage.

Damages are represented in terms of physical damages (e.g., damage states), or percent damage to structures, which is typically translated into economic losses associated with the value of the contents that would need to be replaced. Damage states represent the varying degrees of damage from minor to extreme. Damage states can include qualitative and quantitative descriptions regarding the asset's functionality and physical damage. Note that the percent damage to structures (as represented in many damage functions) does not typically equate to the loss of functionality of an asset, but rather the economic losses (e.g., content replacement costs) associated with a given hazard load.

Climate-related hazards may include riverine and coastal floods, wind and snow storms, temperature extremes, drought, fire, and others. The associated hazard loads can be represented as quantitative estimates of the physical forces to which an asset is subjected. For example, a flood hazard load may be

represented by a certain water depth or water depth and duration; a wind hazard load may be defined as a certain wind speed for a given duration, or a wind pressure on a given structure.

When the relationship between asset damage and hazard load is elastic in nature or is complex, an S-shaped function (or fragility curve) may be used to describe the range of probability of asset damage under a range of loads (Schultz et al. 2010). As shown in Figure 1, an asset may have a series (or 'family') of S-shaped functions where each function represents the probability of failure for a particular wind speed for different percentiles (i.e. percentage of total number of houses above the percentile value). For example, Figure 1 shows that for a wind speed of 17 m/s and damage state I (minor to moderate damage) more than 80 percent of houses have a probability of failure of almost unity, while more than 20 percent of the total houses have the probability of failure in the range of 0.02.

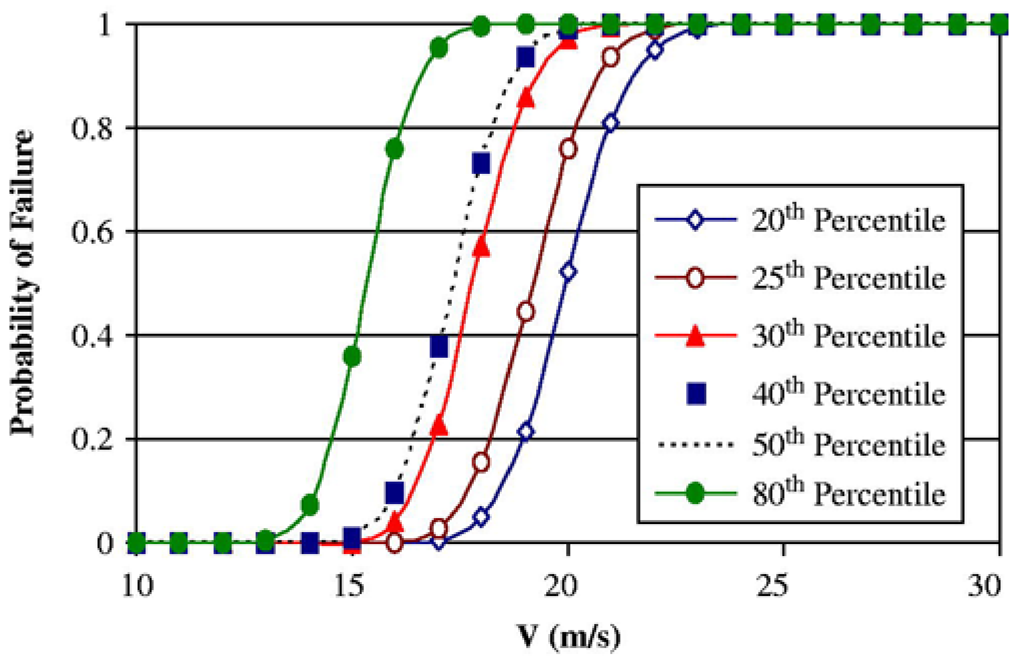


Figure 1. A family of fragility curves showing the overall probability of failures for the 20th, 25th, 30th, 40th, 50th, and 80th percentile for a specific damage state as a function of wind speed (Goyal et al., 2012).[1]

A damage function is a function between 0 (no damage) and 1 (total loss of asset). Even in cases of an extreme hazard load (e.g., flood, high winds), however, there is typically not a complete loss of all material assets. A typical damage function is the depth-damage, or stage-damage, function used for

[1] While this curve is meant to illustrate fragility curves, it is noted in the study that the difference between the fragility curves for different percentiles are not uniform. For example, the fragility curves of 40th and 50th percentile are almost the same, whereas there is a significant difference between 30th and 40th percentile fragility curves. The reason for this is attributed to the ratio of non-engineered to semi-engineered houses, and other factors. Further, it is seen that the fragility curves are very steep showing that within a small range of wind velocity, the probability of failure for any damage state increases from a very low value to almost unity.

flood hazards. It represents the approximate percentage of damage to an asset in response to being exposed to a given depth of flood water.

Fragility curves can be derived from depth-damage curves. One way to derive fragility curves from damage functions is to develop a computational model of the physical process that occurs when an asset is subjected to a load, and then perform an uncertainty analysis of the computational model. This is an expensive, time-intensive, and talent-consuming approach – but sometimes considered the most accurate way to approach the problem.[2] Another way is to use the damage states from depth–damage functions, and apply density functions to each damage state.

There are many sources of damage and fragility curves. The most comprehensive sets of damage curves are associated with specific impact models or disaster events, e.g., the HAZUS model library (over 900 flood-related depth-damage curves for buildings and other assets in the U.S.) and the Multi-Coloured Manual (120 flood-related depth-damage curves for residential, commercial, and industrial buildings in the United Kingdom). Although some fragility curves have been constructed for use in impact assessments (Florida International University, 2005; Burks-Copes et al., 2014), a review of fragility curves (Schultz, 2010) unearthed only 15 instances of fragility curves that had been constructed for climate-related hazards including 13 for flood, and one instance each for wind, and fire, respectively.

Outside of fragility curves that have been developed for use in impact modelling, there are fragility curves that have been developed for structural engineering design and construction applications, particularly for earthquakes, but increasingly for other hazard loads. These curves could theoretically be used to assess damages by plugging them in to any model or assessment that outputs a hazard load (e.g, flood depth, extreme temperatures, snow depth). In Lee and Rosowsky (2005), the authors demonstrate how engineering design curves for snow loads on structures (e.g., reliability-based design) can be converted into probabilistic snow hazard fragility curves (e.g., performance-based design) for the state of Oregon.

However, we did not find instances where 'engineering grade' curves had been integrated into damage or impact models. This is due in large part to the extreme specificity of the engineering-grade curves, which are constructed for particular materials in very specific locations, often focus on the fragility of a particular component of the structure, and typically provide only an extreme damage state (probability of failure). These curves would not be practical to use in a large study area to represent an asset class, for example, but may be useful in consideration of one critical asset where failure or collapse would be detrimental to the mission.

The challenges in achieving an appropriate level of accuracy to the fragility curves is common, particularly for system failures where the consequences may be high, such as a dam or levee breach, or a critical military asset. In the SERDP RC-1701 study, the authors[3] constructed fragility curves for mission critical assets, but indicated that though the development of the curves incorporated engineering

[2] Martin Schultz, USACE, correspondence
[3] Martin Schultz, USACE, Rodriguez, USACE, correspondence

understanding of performance, the curves are not considered accurate enough to be used as a basis for engineering design and construction. Similarly, an initial study on fragility of dams and levees in the United Kingdom (UK) used generalized fragility curves that represented the 61 levee types within the UK National Flood and Coastal Defense Database (Simm et al. 2008). The results of the initial study led to subsequent demands for the development of more accurate, site specific, customized fragility curves for defenses in critical areas such as in the Thames Estuary.

2.1.1 Damage and Loss

Damage and fragility curves are typically integrated into impact models whose primary purpose is to estimate damages and losses to inform planning, stimulate efforts to reduce the risks, evaluate potential hazard mitigation investments, and help in preparing for emergency preparedness, response, and recovery. For many model applications the damages are ultimately represented in terms of total monetary losses, given that planners not only want to understand the risks, but also the total economic losses associated with a hazard event, and the cost effectiveness of different strategies for reducing these losses (Friedland, 2009).

This focus on economic losses is not in complete alignment with the goals and interests of DoD. DoD is primarily interested in understanding whether the ongoing and future ability of military installations to execute missions is at risk (DHS and DoD, 2007); thus, assessing the functionality of 'mission critical' assets is a priority. The 'functionality state' is not a typical component included in damage and fragility information, though some studies have been undertaken with mission execution in mind. For example, Burks-Copes et al. (2014) identified mission critical assets at Naval Station Norfolk, and developed fragility curves where information on asset functionality was included within the damage states. Thus for a particular load, the functionality level of the asset is indicated.

Note that it is generally not recommended to use existing depth-damage curves, or damage states, as a basis for characterizing the physical condition, or functionality, of an asset. For example, flood depth - damage functions are developed by the U.S. Army Corps of Engineers (USACE), Flood Insurance Administration (FIA), and others, to characterize the percent damage to structures in terms of the economic loss. Percent-damage, or even physical damage, does not always equate to, or represent, a functional state. Chadwick (2013) nevertheless assumed some loss of functionality given certain water elevations, and these types of assumptions are also made in the HAZUS model library, but should be verified in practice.

Although the models all assess the degree of direct damages, some of the models provide estimations of indirect losses, though the methodology for these estimates tends to be considerably less rigorous than the direct damage estimations (e.g., several models simply apply a rule of thumb 5-10% of direct damages as representing indirect damages). The indirect economic losses are mainly caused by production losses per economic sector (Hallegate, 2008). For example, HAZUS assesses indirect economic losses including tourism, agriculture, tax revenue, and others. Indirect losses due to system interdependencies and cascading failures (e.g., power failure leading to water failure, etc.) are not considered in the models.

2.1.2 Model Uncertainties

Generally, the different types of model uncertainty can be categorized by the underlying knowledge uncertainty of the current situation or future conditions due to a lack of scientific understanding of the systems and process, a lack of data, and an inability to adequately represent systems and processes. The systems being modeled are complex, and the lack of data quantifying hazard loads and associated asset losses increases the uncertainty of the modeled outcome.

This limitation to our knowledge and our understanding of the processes leads to gross simplifications. For example, modeling the impacts of one hazard load to a single asset confronts us with knowledge uncertainties, given the combination of loadings that can occur (i.e., a given flood hazard may subject a structure to the following loads: velocity, duration, depth). Although in reality, assets may be exposed to many different types of hazard loads simultaneously during an extreme event. In addition, there is uncertainty associated with future climate change, and other future system changes (such as land use).

Addressing uncertainties associated with a lack of data, may in some cases be overcome by improving data collection regarding the specific assets at risk (e.g., their characteristics and contents), and information on past hazard events (e.g., magnitude, location), and their impacts on systems and assets (e.g., loss and damages). For studies that cover large geographic areas, or include a large and diverse array of assets, collecting additional data for all assets may be impractical; however, improving data collection for a representative subset of the assets could help to reduce uncertainty.

Numerous approaches to assessing risks under uncertainty have evolved, including the development of quantitative risk analysis methods such as probabilistic risk assessment, and the more recent 'democratization' of the risk analysis process that provides stakeholders a greater voice in determining relevant uncertainties and risks. Such an 'analytic-deliberative' approach is similar to the methods used to engage stakeholders in integrated water resources management. Because the scientific community generally does not assign probabilities to emissions scenarios, it is difficult to assign full probabilities to particular risks. However, it is possible to assign probability of impacts within an emissions scenario.

The non-stationary nature of climate and other systems requires different techniques for assessing and managing risks. Technical approaches to quantifying the uncertainty in non-stationary systems include importance sampling, fuzzy reasoning, and Bayesian methods. However, not all risk management approaches rely on quantifying uncertainty. Some accept the irreducible nature of some uncertainties and build off adaptive management practices to emphasize learning from the past and building resilience to possible change. Others, such as robust decision making, portfolio theory, scenario analysis and "no-regrets" approaches, focus on making decisions and developing management practices that will offer benefits over a wide range of possible outcomes. Regardless of the approach, risk management must consider the planning horizon and develop plans that appropriately address the investment needs and capacities across various time scales.

A more detailed discussion of uncertainty associated with the models is given by model hazard category, below.

2.2 Reviewed Models and Hazards

Based on the literature review and expert interviews, a core set of relatively well-established, publically available impact models that incorporate damage and/or fragility curves was identified. Note that the review of impact models is limited to: 1) models that incorporate damage and fragility information; and 2) models that can be used for vulnerability assessments at levels above the most detailed engineering-level analysis as described in Section 1.2, above. Within the impact models, only two hazards were identified that are incorporated into the damage and fragility curves: flood and wind. Although no publically available models were found that included damage and/or fragility curves associated with other climate-related hazards, several studies were identified that quantify infrastructure damages associated with other hazards, and these are described separately. As shown in Table 1, the review includes twelve flood impact models and two wind impact models.

Table 1: Damage and fragility models of infrastructure assets

Hazard	Model	Location
Flood	HAZUS-MH 2.1	United States (U.S.)
	Flood Loss Estimation MOdel (FLEMOps, FLEMOcs)	Germany
	Damage and Victims Module (HIS-SSM)	Netherlands
	Damage Scanner Model	Netherlands
	Rhine Atlas Damage Model (RAM)	Rhine Basin, Europe
	Flemish Model	Belgium
	Multi-Coloured Manual	Europe
	Loss prediction model	Australia
	Riskscape	New Zealand
	Joint Research Centre (JRC) Model	Europe
	Flood Damage Reduction Analysis (HEC-FDA)	U.S.
Wind	HAZUS-MH 2.1	U.S.
	Florida Public Hurricane Loss Projection model (FPHLP)	Florida, U.S.

The development and application of a screen based on a set of criteria was applied to the models, to better inform the review. These criteria were developed to help to quickly identify the strengths and weaknesses of the models, their purpose, the underlying damage and fragility information, and ultimately, their applicability to the assessment of military installations given different contexts and identified assessment needs. The following outlines a sub-set of the fifteen criteria[4] used to catalogue each of the models, providing a basis for inter-comparison, and better enabling users to identify models that may fulfill assessment needs:

- Model Objective: Purpose of the model
- Damage and/or Fragility Information:
    - Climate Hazard Load (e.g., wind velocity, water depth)

[4] See Appendix C

    - Assets (e.g., buildings, transportation)
- Geographic Area: Applicability of the model to different geographies or places
- Details on Damage Assessment by DoD Facility Class
- Indirect Impacts Assessed
- Uncertainty: Identified Areas of Uncertainty in the Approach

The models were evaluated based on information found in model manuals and reports, model application studies, other published model reviews, and conducted interviews. A model catalogue was developed in Microsoft Excel to organize the information, provide a basis for inter-comparison, and ensure that the information is easily accessible. Within the model cataloguing, there is a strong emphasis on understanding the fragility and damage curves, including the various combinations of the types of infrastructure and hazards addressed, and how the damages to these infrastructure types are assessed. The assets that are considered within the models and fragility and damage curves are classified based on the DoD Real Property Classification System (RPCS)[5]. A number of models had limited information available describing the assets and indirect impacts that were covered, limiting the depth of comparison. The information gathered in the model catalogue is synthesized and presented in this report in the detailed analysis of the flood and wind models, below.

2.2.1 Flood Impact Models

The primary purpose of flood impact models is to make flood loss estimations for decision makers at local, regional, or national scales. This is accomplished by assessing the risk of flood losses (e.g., identifying asset damage and other vulnerabilities to floods). These loss estimates can inform planning, stimulate efforts to reduce flood risks, evaluate potential flood defense investments, and help in preparing for emergency response and recovery.

We identified twelve flood impact models that integrate damage and fragility information to assess asset losses and damages given a flood event (see Table 2). These models include riverine and coastal flooding, and cover different geographic locations. The focus of the model review was to better understand the characteristics of the damage and fragility information embedded within the models, and to identify which of the models included damage information that might be applicable to assets at military installations.

As shown in Table 2, each flood impact model was developed for various purposes in various geographic locations using a variety of flood damage information. Some of these models may only be applicable in certain geographic regions (e.g., depth-damage information developed after a specific flood event for a European city situated along the Rhine River).

[5] See Appendix D

Table 2. The purpose and general flood damage, fragility, and/or functionality Information embedded in each of the 12 flood impact models.

	Models	Model Purpose	Types of Damage, Fragility, and/or Functionality Information
United States	Hazards U.S. Multi-Hazard (HAZUS-MH 2.1)	Provides a means for planning and simulating mitigation efforts to reduce losses from severe floods at the local, state, and regional level; a secondary purpose is to provide a basis for assessing nationwide risk of flood losses	Flood Hazard: Riverine and coastal flooding Hazard loads: Flood depth, Flood velocity, Flood debris Assets: Covers many of the assets provided in the Real Property Classification Scheme (RPCS) at the Tier 3 level Damage Information: Over 900 depth-damage curves for residential buildings, commercial buildings, and critical utilities (i.e., potable water systems, wastewater systems, oil systems, natural gas systems, electrical power systems, communication systems); Functionality information provided for critical utilities; Fragility and functionality information provided for bridges; 12 velocity-depth damage curves for buildings; Flood debris damage information as a function of the depth of flooding, building square footage, and the foundation distribution information; user-defined is an option. Damage curves are based on empirical data from past events, expert judgment, and synthetic approaches. Damages and losses: Direct economic losses (structure, contents, shelter, fatalities); Indirect economic loss (tourism, loss of tax revenue, and impacts on agriculture)
	Hydrologic Engineering Center's Flood Damage Reduction Analysis (HEC-FDA)	Provides a detailed economic assessment of damages (damages avoided) and benefits attributed to flood control projects from a single riverine flood event or a longer period of record. This model stores hydrologic and economic data for the analysis, provides tools to visualize data and results, computes expected annual damages (associated with a given analysis year) or the equivalent annual damage over the project life of the plan, annual exceedance probability and conditional non-exceedance probability as required for levee certification, and implements the risk analysis procedures.	Flood Hazard: Riverine flooding Hazard Loads: Flood depth Assets: User-defined Damage information: User-defined, can create up to 20 damage categories with sub-categories (e.g., residential category with a subcategory of one-story single family, no basement and raised foundation), user-defined functions can be provided or ones from HAZUS can be used. Damage information can be based on empirical information, expert judgment, or synthetic approaches. Damages and Losses: Direct economic losses (structure, content)

	Models	Model Purpose	Types of Damage, Fragility, and/or Functionality Information
Europe	Flood Loss Estimation MOdel (FLEMOcs, FLEMOps)	Provide estimates of losses to residential buildings, commercial buildings, equipment and goods, products and stock of companies	Flood Hazard: Riverine flooding Hazard Loads: Flood depth Assets: Residential buildings (three different building types at low/medium and high quality), commercial buildings (e.g., mining and quarrying, electricity, gas and water supply, hotels and restaurants, agriculture, manufacturing, construction) Damage information: 6 depth-damage curves for residential based on a surveys and empirical data of flood loss from past events; 12 depth-damage curves for commercial based on based on analysis of 2002, 2005 and 2006 floods in Germany Damages and Losses: Direct economic losses (buildings, equipment and goods, products and stock of companies)
	Damage and Victims Module (HIS-SSM)	Estimate potential flood damage on a regional or national scale and calculate economically efficient investments in flood defenses	Flood Hazard: Riverine and coastal flooding Hazard Loads: Flood depth, flood velocity Assets: Cars, roads and railroads, electricity and communication, industry, low-rise buildings, medium-rise buildings, high-rise buildings, single family houses or farms Damage information: 11 damage functions are derived using a synthetic approach based on expert judgment and empirical data of flood loss (e.g. from the insurance industry or engineers' estimates of the amount of damages that would occur at a specific element at risk under certain flood conditions) Damages and Losses: Direct economic losses (structures, casualties, trade) and indirect economic loss (percent of direct loss)
	Damage Scanner Model	Provides an aggregated approach for regional analysis (instead of the detailed HIS-SSM) to estimate flood damage	Flood Hazard: Riverine flooding Hazard Loads: Flood depth Assets: HIS-SSM assets aggregated to land use data Damage information: 7 depth-damage curves based on information provided in the HIS-SSM Damages and Losses: Direct economic losses (structures) and indirect economic losses (percent of direct loss)
	Rhine Atlas Damage Model (RAM)	To identify flood risk performance targets within the Rhine area.	Flood Hazard: Riverine flooding Hazard Loads: Flood depth Assets: Residential, equipment, industry, infrastructure, agriculture, forest, other Damage information: 11 depth-damage functions developed from expert discussions and empirical data Damages and Losses: Direct economic losses (structure, content)

	Models	Model Purpose	Types of Damage, Fragility, and/or Functionality Information
	Flemish Model	Assessing regional and national scale damage developed specifically for aggregated land use data. The model identifies vulnerable areas and calculates efficient flood defense investments.	Flood Hazard: Riverine flooding Hazard Loads: Flood depth Assets: Residential, industry, infrastructure, recreation, agriculture, pasture, nature/forest, water Damage information: 11 depth-damage curves developed based on expert discussions (high-level damage classes) Damages and Losses: Direct economic losses (structures, content) and indirect economic losses (percent of direct loss)
	Multi-Coloured Manual	To support water management policy and enable quantitative assessment of the effect of investment decisions	Flood Hazard: Riverine and coastal flooding Hazard Loads: Flood depth, flood duration Assets: Retail, commercial, industrial and residential Damage information: 120 absolute depth-damage curves (i.e., monetary loss as a function of damage) Damages and Losses: Direct economic losses (structures, content, clean-up) and indirect economic losses (evacuation, loss of utilities, etc.)
	Joint Research Centre Model (JRC Model)	To assess flood loss	Flood Hazard: Riverine and coastal flooding Hazard Loads: Flood depth Assets: Residential, commercial, industrial, roads and agriculture Damage information: 5 depth-damage functions developed from data across 9 EU-27 countries Damages and Losses: Direct economic losses
Australia and New Zealand	Loss prediction model[6]	To consider flood waters damage to buildings, and highlights the role building and planning controls can play in exacerbating or mitigating this damage	Flood Hazard: Riverine and coastal flooding Hazard Loads: Flood depth Assets: Residential houses Damage information: 4 empirically adjusted depth-damage curves for residential houses based on 11 depth-damage functions developed using a synthetic approach Damages and Losses: Direct economic losses

[6] Mason, MS, Phillips, E, Okada, T & O'Brien, J 2012, Analysis of damage to buildings following the 2010–11 Eastern Australia floods, National Climate Change Adaptation Research Facility, Gold Coast, 95 pp.

	Models	Model Purpose	Types of Damage, Fragility, and/or Functionality Information
	Riskscape[7]	To calculate the risk of impact to assets due to floods. Risk information can then inform decision making for a range of natural hazard management activities including land-use planning, emergency management, asset management and insurance.	Flood Hazard: Riverine flooding Hazard Loads: Flood depth, flood duration, flood velocity Assets: Commercial, industrial, farming and horticulture, forestry, tourism, critical facilities, buildings, utilities, transport Damage information: Fragility curves with five damage-states based on post-event impact surveys and a damage/weather catalogue Damages and Losses: Direct economic losses (structures, content, clean-up) and indirect economic losses (evacuation, loss of utilities, etc.)

[7] https://riskscape.niwa.co.nz/

To fully determine flood risk of assets at a military installation, three components should be considered: (1) the probability and characteristic loadings of a flood event, (2) the value and susceptibility of the assets to physical damages or functional losses as a result of the hazard loads, and (3) the capacity of the installation to deal with the event to reduce vulnerability (adapted from Jongman et al. 2012a citing Kron 2005). The first two of these three components are useful to the impact assessment (i.e., modeling the impact of military assets at an installation to flooding), and are central to the fragility and damage information integrated into the flood impact models. Though, the future probability of specific flood loading magnitudes is uncertain given climate change, and should be recognized when undertaking the analysis. The flood models cited in the table address the second component regarding susceptibility of the assets. Some of the flood models, such as HAZUS, also come equipped with flood depth associated with “canned” flood events that are hardwired into the model and can be run for varying types of floods. The third component, capacity to deal with the event, is provided in a few flood models where the user can insert specific mitigation strategies and then test the corresponding change in flood depth.

2.2.1.1 Damage and Fragility Information

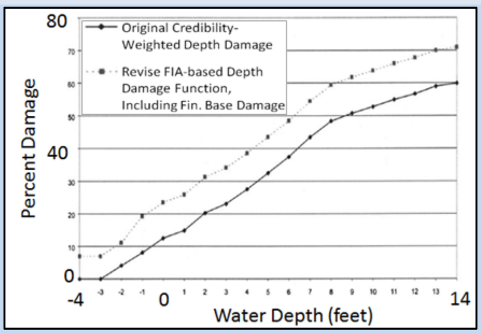
As described above, fragility and damage information can be developed via expert judgment, observations, models, and a combination of approaches (Schultz, 2010). For flood applications, this information includes (adapted from IWR, 2013):

- Expert judgment of the degree of physical damages and associated economic losses for a given flood based on surveys and interviews;
- Historical data and observations of flood depths, asset damages, and asset functionality loss;
- Modeled “data” of physical damages and associated economic or functional losses of assets for a given flood depth; and
- Existing data of economic asset value, losses and damage from prior studies, Federal Emergency Management Agency (FEMA) reports, and National Flood Insurance Program (NFIP) databases.

All of the reviewed flood impact models rely predominantly on damage information (i.e., in particular, depth-damage curves) to provide a sense of economic losses associated with a specific water depth. An example of a depth–damage function is provided in Box 1.

Box 1. Depth-Damage Information

Depth-damage information is typically provided in two forms (Figure A): (1) curves developed from percent damage per depth of water depth (the left-hand graph); (2) tables with percent-damage provided as discrete values per depth of water depth (the right-hand table). The residence considered in the depth-percent damage curve illustrated in Figure A (left) is two or more stories with a basement. For values below 0, the water depth may impact the basement. For values above 0, the water depth affects the first or second story of the building. The convex shape of the function is characteristic of these curves, in that significant damages occur at low flood levels and the marginal increase in damage declines at higher flood levels.



Functionality Threshold Depth	Percent Damage by depth of flooding in feet											Comments
	0	1	2	3	4	5	6	7	8	9	10	
4	0	0	0	0	40	40	40	40	40	40	40	Assumes entrance is 3 feet above ground level and is not sealed. Assumes all electrical equipment is below grade. Once entrance level exceeded, entire pump station floods

Figure A. Left: FIA-based structure depth-percent damage curve, two or more stories, basement modified. (Scawthorn et al., 2006). Right: Depth-percent damage and functionality of a lift station for wastewater. (FEMA, 2009).

The table describes the percent damage per foot of water depth for a lift station. For this asset, it is assumed once the water level surpasses 3 feet, the lift station will be flooded and no longer functional. Hence, this table provides both percent damage and functionality information.

The use of fragility information, though increasing, is still under-represented in the reviewed models, and in practice. The flood risk community tends to isolate the use of fragility curves to describing the probability of failure associated with hydraulic structures like dams. This is because of the significant damage that could occur if one of these major structures were to lose functionality and the importance of probabilistic information regarding such failure. This is unlike the analysis of numerous assets that may be flooded where the flood impact model is simply concerned with estimating the level and cost of the flood damage to all assets within the flood plain. Nevertheless, a few standard fragility curves are available for use in HAZUS-MH, and the HEC-FDA has developed and employed customized fragility curves to better understand the failure of hydrologic structures such as dams and levees.

In fact, though not as wide spread as the use of damage curves, the use of fragility curves have become more common for high-consequence flood impact modeling (from Schultz (2010): Hall et al. (2003), Gouldby et al. (2008), Apel et al. (2004)). For example, the USACE developed fragility curves for earthen levees and floodwalls to model flood risks (including levee failure) in New Orleans, using the USACE' prediction models WAve prediction Model (WAM), Steady-State Spectral Wave (STWAVE) model, and ADvanced CIRCulation Model (ADCIRC) (IPET, 2009). In the UK, a hybrid approach (involving engineering

judgment, observations, and analytical methods) was developed and applied to better understand flood defense failure modes and to develop associated bespoke fragility curves (Allsop et al., 2007; van Gelder, 2008; Simm et al., 2008; Flikweert and Simm, 2008).

An example analysis of site-specific high impact flood damage information is one that was led by the USACE developing the following flood damage information for Donaldsonville, Louisiana. The hazards considered include: riverine or rainfall flooding (freshwater) for 1 day or less, riverine or rainfall flooding (freshwater) for 2 to 3 days, hurricane flooding (saltwater) for 1 day, and hurricane flooding (saltwater) for 2 weeks. The damage information developed from interviews with homeowners, business operators, and experts included estimates for: depth-damage for residential and commercial structures, depth-damage for contents, depth-damage for vehicles, and content-to-structure value ratio (CSVR) (USACE, 2006)[8]:

- Residential structures were divided into one-story on pier, one-story on slab, two-story on pier, two-story on slab, and mobile home categories.
- Commercial structure types were categorized as metal frame walls, masonry bearing walls, and wood or steel frame walls.
- Residential contents were evaluated as one-story, two-story, or mobile home.
- Commercial content categories included the following types: eating and recreation, groceries and gas stations, multi-family residences, repair and home use, retail and personal services, professional businesses, public and semi-public, and warehouse and contractor services.

An interesting facet of this study was that it included damages not just by depth but also considered the additional impact of saline water. For the best results, the fragility and damage information should be representative of the specific location and hazard loads, and also include the desired damage information (e.g., economic losses, loss of functionality, etc.). Undertaking this type of analysis in the aftermath of a high impact event on a military installation, could provide useful information for DoD, and support an installation or detailed level assessment. Alternatively, DoD could use the fragility and damage information available in the reviewed models to inform an installation or detailed assessment.[9] This typically requires careful calibration to assets on military installations both in the amount of damage per hazard load as well as the asset value, though the standard information may not include the desired damage metrics or hazard loads. The following sections take a closer look at the available hazard loads and damage information.

2.2.1.2 Hazard Loads

In general, causes of flood events include: heavy rainfall, snowmelt, tsunamis, storm surges, ice jams, and failure of hydraulic structures (e.g., dams, levees) (IWR, 2013). Associated with these flood events are a number of flood-related hazard *loads* that can lead to asset damage: depth of floodwater, velocity

[8] The damage curves can be accessed in this report.

[9] For example, the depth-percent damage relationship is meant to apply to specific asset classes. At the most basic level, the percent damage can used to determine asset specific damages if the asset value is known

of floodwater, duration of flooding, and debris/sediment load (Davis and Skaggs, 1992; IWR, 2013). Flood depth is the most common hazard load considered in the flood models.

The impact models reviewed here only capture some of the hazard loads (see Table 2), and typically consider only the impact of a single load. There are scientific challenges in properly considering the combined potential for riverine and coastal flooding, and the associated flood hazard loads. Fully coupled, or at least loosely coupled, riverine and coastal models are needed. HAZUS-MH is the only model to consider the combined impact of hurricane winds, storm surge, and waves on building loss. The primary purpose is to avoid "double counting" when a building is damaged by both hurricane and flood hazards during a hurricane event.

The HAZUS-MH and the Damage and Victims model are the only models that consider flow velocity. A study, based on limited data, suggests that the flow velocity in water more than 2.4 m deep can increase losses by 2 to 5 times compared to the losses associated in conditions without significant flow velocity (Mason et al., 2012 citing McBean et al., 1988). The velocity-based building collapse curves available in HAZUS-MH relate the potential of a building collapse to riverine-related overbank flow velocity and water depth for three building material classes (wood frame, steel frame, and masonry or concrete bearing wall structures) and at multi-stories (1-story, 2-story, 3-story, 4-story) (see Figure 2). Similar information does not exist for essential facilities (i.e., medical care facilities, emergency response, and schools), high potential loss facilities (i.e., dams, nuclear facilities), or critical utilities (i.e., potable water systems, wastewater systems, oil systems, natural gas systems, electrical power systems, communication systems).

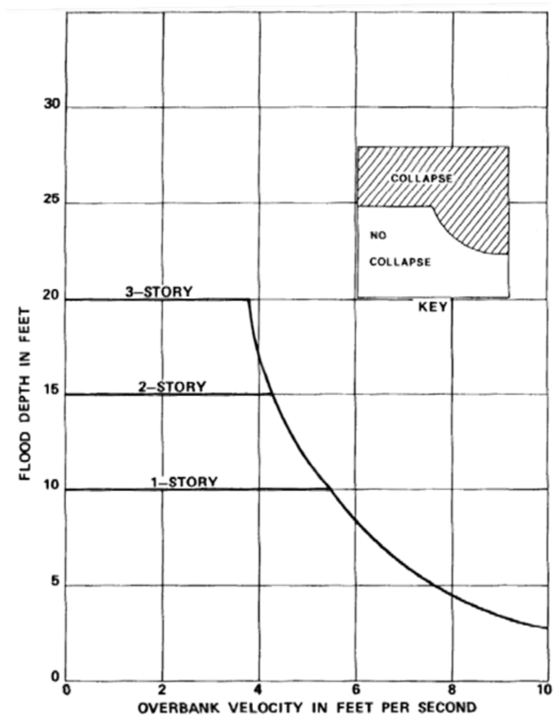


Figure 2. Building collapse curve for wood frame buildings developed by the USACE Portland District (USACE, 1985).

In addition, HAZUS-MH provides a module that estimates the amount of debris in tons that would be generated from content and finishes within the structures at a census block level based on the depth of flooding for that census block, building square footage of each residential/ commercial building stock, and the foundation distribution information. An exception is if the flood damage is above 50%, whereupon total debris would include the structural components (Scawthorn et al., 2006).

2.2.1.3 Damage and Loss

A primary purpose of flood impact models is estimating direct and indirect economic losses associated with varying flood inundation levels with/without flood mitigation (e.g., for benefit-cost analyses). This is useful to DoD if cost-benefit analyses are needed in the assessment to consider what assets may

become most costly under future climate scenarios to repair/replace, and what measures may be useful for mitigating losses. This type of information helps to direct planners towards important primary adaptation considerations.

The reviewed flood impact models are typically limited to estimating direct economic losses associated with commercial and residential buildings. The flood impact models can be used to estimate a variety of direct and indirect damages and losses associated with flood-related loads: structure and content damage, loss of production and income, and loss of life and trauma (IWR, 2013; Jongman et al., 2012b citing Smith and Ward, 1998; Messner et al., 2007; Merz et al., 2010; Bubeck and Kreibich, 2011). The damages and loss information is associated with physical damages, loss of functionality, or other economic losses as described below.

The direct economic losses include asset and social losses, and include considerations of asset structure repair and replacement costs. The categories of losses covered by flood impact models may include:

- Building structure loss (e.g., building repair and replacement costs based on the value of the building);
- Building content loss (e.g., building content value is generally estimated as a percent of the structure replacement value);
- Additional building-related losses (e.g., relocation expenses, loss of income, employment-related losses, and rental income loss);
- Critical utilities (e.g., potable water systems, electrical power systems, communication systems);
- Social loss (e.g., loss of shelter and fatalities).

In general, monetary losses associated with building structure and critical utility losses are estimated using depth–percent damage curves, wherein the percent damage multiplied by the value of the asset equals the economic loss. The economic losses for each asset are aggregated up to provide a total economic loss. A “uniform” value of an asset, e.g., a building, may be determined based on such factors as square footage, construction type, number of stories, existence of a basement, etc.[10] Further, depreciation of the structure may be available based on the condition of the asset (e.g., poor condition, average condition, good condition).

The estimated monetary losses and percent-damage do not simply equate to loss of functionality of the asset (e.g., for a given asset, will 20% or 40% of damage equate to loss of functionality; and how long will the functionality be lost – a day, a week?). Expert guidance is required to translate the depth-damage information into functionality loss as a function of time post-event as this translation would be different by asset type and location. As presented in Table 2, most of the flood impact models do not

[10] For utility systems, the estimated loss ($) of an asset may be estimated by the percent damage based on flood water depth with the value of the asset. The percent damage is constructed from the depth of water in reference to the equipment height. For a given asset which may be defined in actuality more as a facility that houses an aggregate of smaller assets, the most critical asset to functionality and loss is considered (e.g., wastewater treatment plant will have a collection of assets of varying sensitivity to flooding).

consider functionality. HAZUS-MH flood model does identify asset functionality loss by assigning a percent-damage value by asset when functionality will be lost (see Section 4).

Indirect losses include additional economic disruption not captured by the direct losses described above, such as from tourism, loss of tax revenue, and impacts on agriculture. Indirect loss estimates have greater uncertainty than direct loss estimates as they are more difficult to verify, require economic modeling, and are sensitive to additional factors such as economic resiliency (FEMA, 2009).

2.2.1.4 Asset Coverage

To illustrate the military asset coverage, we used DoD RPCS that is used by the Real Property Asset Database (RPAD), to provide a list of important assets at military installations. The RPCS provides a 5-Tiered structure of asset categories. [11] We conducted our crosswalk at the RPCS Tier 3 categorizations and used this information for our "cross-walk" against the assets covered by each of the flood impact models. We then aligned the assets covered by each flood impact model's damage information with the RPCS Tier 3 categories. The results were then aggregated up to the RPCS Tier 1 level for comparison across flood impact models. Table 3 presents a high-level summary of the asset types that are covered by the reviewed flood impact models

Notice that even though some of the flood impact models may be constructed to cover many of the asset classes, they typically require the user to provide asset attributes, such as whether the building is made of wood or concrete to select the appropriate damage curves (if not relying on the default inventory provided by some of these models). For HAZUS-MH, this required asset information is discussed in further detail in Appendix B, which provides a detailed cross walk of asset coverage for the HAZUS-MH Flood model.

[11] An example of the Tier structure within the RPCS is as follows for an airport runway: Tier 1 categorization is "Class 1: Operation and Training", Tier 2 is "11 Airfield pavements", and Tier 3 is "111 Airport runway." As the information provided by each of the flood loss model allowed, we compared the asset information in the flood loss model against the assets at the RPC Tier 3 level.

Table 3. Coverage of DoD facility class assets in the reviewed flood impact models. Results are aggregated to RPCS Tier 1 level (e.g., "Operations and Training"). Grey shading indicates 'no coverage'; Yellow shading indicates that the model provides damage information at the Tier 1 level) and does not provide damage information at a finer scale; Orange shading indicates there is only "low coverage" with less than one-third of Tier 3 assets represented for a respective Tier 1 category ; light red shading indicates 'medium coverage' with less than two-thirds of Tier 3 assets represented within the Tier 1 category; and red shading indicates 'high coverage' with more than two-thirds of Tier 3 assets represented within the Tier 1 category.

Flood Model	RPCS Classification Categories of Tier 1 Classification								
	Operation and Training	Maintenance and Production	Research, Development, Test, and Evaluation	Supply	Hospital and Medical	Administrative	Housing and Community	Utility and Ground Improvements	Land
HAZUS-MH 2.1 (also used as input to HEC-FIA and HEC-FDA)									
Flood Loss Estimation MOdel for the commercial sector (FLEMOcs)									
FLEMOps									
Damage and Victims Module (HIS-SSM)									
Damage Scanner model									
Rhine Atlas damage model (RAM)									
Flemish Model									
Multi-Coloured Manual (United Kingdom)									
JRC Model									

A number of flood impact models, particularly the European-based models, have limited information available describing the potential damages that may be covered at Tier 3 asset classes. For example, instead of providing damage functions for each type of asset within the industrial sector, industry may be covered by one damage function based on aggregated data of industry flood damage after an event. Because of this, only a low level comparison between the flood impact model and RPCS Tier 1 asset categories was possible, resulting in either grey or yellow shading. HAZUS-MH provides detailed asset damage information allowing for a higher level comparison (i.e., resulting in matches in orange through red shading as described in Table 2). Overall, the HAZUS-MH model has the best coverage of damage information for the majority of DoD assets at military installations.

Overall there are limitations and gaps in the flood damage information that these flood impact models provide. Specifically, flood damage information for the following assets found at military installations is not available: training facilities, armory, supply (e.g., liquid storage, cold storage), and waterfront infrastructure (e.g., pier).

It should be noted that for the models with well detailed technical manuals, like HAZUS-MH, the RPCS Tier 3 level was the optimum level for the crosswalk against the damage functions. This further suggests an important point: the damage functions discussed in this section would be useful for an assessment at a similar asset level. We did not find an available approach for aggregating this information “up” for DoD to use in a RPCS Tier 1 or Tier 2 level analysis approach (e.g., binning assets with like depth-damage relationships and associated threshold functionality).

2.2.1.5 Areas of Uncertainty

There are a number of areas of uncertainty associated with estimating asset sensitivity to riverine and coastal flood inundation listed below.

(1) Identifying asset damage function:

- The largest collection of asset depth-percent damage functions is housed in the HAZUS-MH flood impact model. The applicability of these depth-percent damage functions at a given location or outside of U.S. boundaries is not clear and will likely vary by the depth/scope of the vulnerability assessment and unusual sensitivities of the individual assets, requiring local expertise.
- In evaluating flood damage, the USACE (2003) suggests that percent damage is more applicable across geographic location, though the value of economic losses (a derivative of percent damage that relies on estimating building content replacement values) is more useful when applied to particular buildings for a specific time.
- In terms of utilizing depth-damage percent curves associated with residential buildings, though the damage curves may be applied to a single building as well as to all buildings of a given type, they are more reliable as predictors of damage for large, rather than small groups of buildings (an actual asset may behave differently than anticipated due to prior damage, etc.).
- An extreme weather storm may damage a structure both through flood inundation and wind. Because the damage occurs under synergistic conditions, it can be challenging to tease out which part of the structure damage is associated with each hazard.

- Another primary source of uncertainty pertains to the building properties assumed, including the strength of components, the variability of construction techniques and quality, materials used, effects of aging, load path assumptions, and other considerations.
- Because assessment of damage to contents is highly dependent on the rain intensity of the hurricane and the fact that a structure might experience leaks even without envelope breach, estimate of contents damage also involves a lot of uncertainty.

(2) Additional considerations:

- Hazard Exposure: Flood damage is generally calculated by depth of flood, yet, depending on storm and location, a number of other factors may be important such as time of year the flood occurs, velocity of the floodwater, the duration of the flood, sediment loads, and warning time (USACE, 2003). In addition, the future probability of specific flood loading magnitudes is uncertain given climate change.
- Future Development: The applicability of damage function data as development changes is limited (i.e., depth-damage data is often not being updated regularly to account for future development and land use changes).

Estimating Costs: Some critical issues regarding cost uncertainties include estimations of repair costs, due to uncertainties in the correspondence between actual physical damage and cost projection. Improved data collection on the assets at risk, and on historical flood risks and damages can help to reduce some of the uncertainties, above. In instances where risk and consequence (e.g., losses) are perceived to be high, data collection on the asset or system at risk may reduce underlying uncertainties, and improve system understanding.

Management of flood risks requires an understanding of the current situation and recent trends, and should involve forecasting possible futures, recognizing that knowledge is imperfect and incomplete. Since climate and water are non-stationary, different techniques can be employed to quantify uncertainty, such importance sampling, fuzzy reasoning, and Bayesian methods. Other techniques accept the irreducible nature of some uncertainties, and allow for consideration of a wide range of possible outcomes, including robust decision making, and scenario analysis. For example, scenarios can be developed or employed that reflect different possible futures, and integrated into fragility and damage modeling. Monte Carlo and Bayesian approaches are useful for capturing statistical uncertainty.

2.2.2 Wind Impact Models

We identified two publicly[12] available wind loss models in our review: the HAZUS Wind Model ('HAZUS Model') and the Florida Public Hurricane Loss Model ('Florida Model'). The HAZUS Model is widely used by federal, state, regional and local governments to produce damage risk and loss estimates for hurricane risk mitigation, emergency preparedness, response and recovery (FEMA, 2009). The Florida Model estimates economic losses and probable maximum economic losses from hurricane events for residential and commercial property.

Table 4 lists the models, including their primary purpose, and major characteristics. These characteristics are covered more fully in the following sections.

[12]For a list of other models covering Florida, including private models, please see: https://www.sbafla.com/method/ModelerSubmissions/CurrentYear2011ModelerSubmissions/tabid/1512/Default.aspx

Table 4. Reviewed wind impact models.

Models	Model Purpose	Types of Damage, Fragility, and/or Functionality Information
HAZUS-MH MR5	Produce economic loss estimates for use by federal, state, regional and local governments in planning for hurricane risk mitigation, emergency preparedness, response, and recovery	Wind hazard: hurricane Hazard loads: wind velocity and duration, rainfall, airborne debris, tree blowdown Assets: residential, commercial, industrial, essential facilities, trees Damage Information: modeled, validated with insurance loss data where possible Damages and losses: direct economic losses (structure, contents, loss of functionality); indirect loss of shelter Location: United States
Florida Public Hurricane Loss Model ('Florida Model')	Estimates economic losses and probable maximum economic losses from hurricane events for residential and commercial property to improve the accuracy of insured Florida loss estimates for use in residential rate filings and probable maximum loss calculations	Wind hazard: hurricane Loads: wind velocity, airborne debris Assets: commercial and residential buildings Damage Information: based on a component approach that combines engineering modeling, simulations with engineering judgment, and observed (historical) data Damages and losses: direct economic losses and probable maximum losses Location: Florida, USA

2.2.2.1 Damage and Fragility Information

The wind impact models rely on damage functions to provide an estimate of economic losses associated with a specific wind speed. The resistance offered by a structure is typically calculated on a component-wise basis (e.g., roof, windows) with parameters derived using the following techniques (Vickery, 2000a; Vickery, 2000b):

- Engineering judgment of the degree of physical damages and associated economic losses for a given wind event, based on surveys and interviews;
- Historical data and observations of wind speeds, debris analysis, tree blowdown, and asset damages;
- Modeling and engineering analysis of physical damages and associated economic losses of assets for a given wind speed, and airborne debris ('windborne missiles'); and
- Laboratory tests.

2.2.2.2 Hazards and Associated Loads

The models currently only cover hurricanes; although, the HAZUS model will eventually cover extra-tropical cyclones, tornadoes, and thunderstorms and hail[13]. Different levels of analysis are offered by the models- including probabilistic, scenario, and historical storms.

The hazard loads associated with hurricanes, include wind pressure, windborne missiles, rain, storm duration, storm surge, waves and atmospheric pressure changes. Currently, the HAZUS and Florida models consider wind speed, airborne missiles (e.g., gravel, shingles), and rain (damage to interior). HAZUS-MH MR5 also includes storm duration and tree blow down.

2.2.2.3. Damage and Loss

The reviewed wind impact models are typically limited to estimating the direct economic losses to building value and content replacement costs of commercial and residential buildings; however, the HAZUS model does include the indirect 'loss of shelter'.

The HAZUS model calculates the probability of each of five discrete levels of damage for every structure in the study region for a given wind speed, using fragility curve parameters specific to that building. The five damage states for buildings are: no damage, minor damage, moderate damage, severe damage and destruction (Vickery, 2006b). See Figure 3.

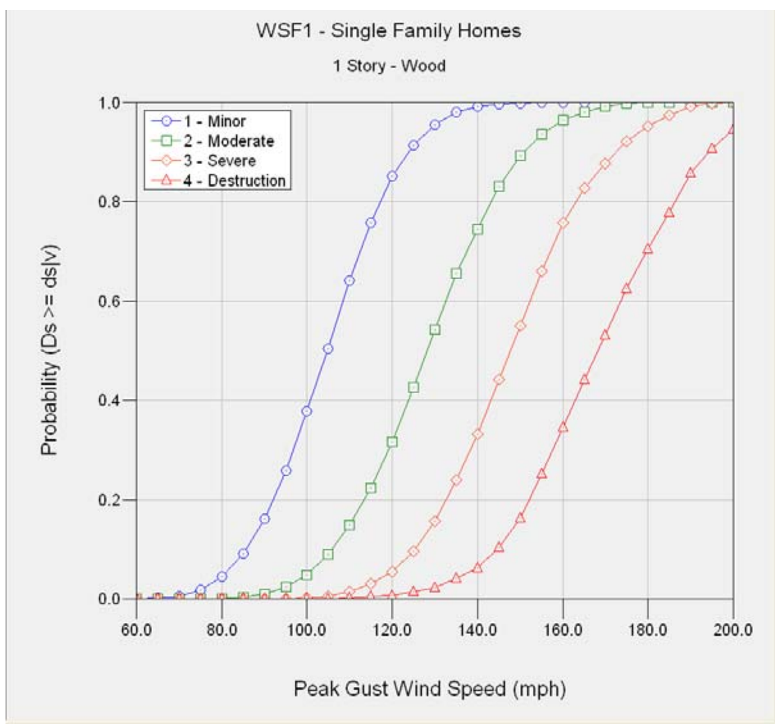


Figure 3. Fragility curves in the HAZUS model representing 4 damage states for a 1 story, wood frame home.

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[13] Personal communication, Eric Berman (FEMA), no timetable indicated.

The Florida Model provides information in a ‘vulnerability matrix’, which can be thought of as damage table indicating a mean damage ratio for a given wind speed (see Figure 4). The model can also generate fragility curves (the probability of exceedance of any given damage level as a function of the wind speed) for each damage table, though these curves are not used in the model (EQECAT, 2013). The internal and content damage are extrapolated from the external damage on the basis of expert opinion and are confirmed using historical claims data and site inspections of areas impacted by recent hurricanes. The contents losses are estimated as a proportion of total estimated interior damage to the building, where interior damage is determined by the expected number of openings per story to be breached, and the resulting volume of water intrusion in each story.

Damage (%)/Wind Speed (mph)	47.5 to 52.5	52.5 to 57.5	57.5 to 62.5	62.5 to 67.5	67.5 to 72.5
0% to 2%	1	0.99238	0.91788	0.77312	0.61025
2% to 4%	0	0.00725	0.0806	0.21937	0.36138
4% to 6%	0	0.00037	0.001395	0.007135	0.0235
6% to 8%	0	0	0.000125	0.000375	0.0025
8% to 10%	0	0	0	0	0.000375
10% to 12%	0	0	0	0	0.000375
12% to 14%	0	0	0	0	0.000625
14% to 16%	0	0	0	0	0.0005
16% to 18%	0	0	0	0	0.000125
18% to 20%	0	0	0	0	0.00012
20% to 24%	0	0	0	0	0.00025
24% to 28%	0	0	0	0	0

Figure 4. Example of mean damage percent of residential house given 3 second gust wind speed at 10 meters height in the Florida Model (EQECAT, 2013).

Although the wind models do not assess damages to nonstructural assets within the buildings (such as kitchen cabinets and carpeting), they include these losses in estimating associated costs. For example, repair costs can be assigned to nonstructural components for a particular damage state.

2.2.2.4 Asset Coverage

Currently only damage curves for buildings are included in the reviewed wind loss models. Although, this can be quite extensive in terms of the number of assets. For example, general building stock types in HAZUS include residential, commercial, industrial, agricultural, government, and educational categories, each of which include several sub categories, and can also be catalogued by materials and other characteristics (e.g., roof type). For DoD purposes, the HAZUS wind model offers the most complete coverage, albeit restricted to the general building stock. The Florida model includes some commercial real-estate as well as residential housing.

Power systems represent another asset where losses due to high winds have been modeled, but a universal, publically available model was not found in our review[14]. Resilient Electricity Networks (RESNET), an ongoing project in the UK, is in the process of developing a comprehensive approach to analyze, at a national scale, climate-related changes in the reliability of the UK's electricity system, and to develop tools for quantifying the value of adaptations to enhance its resilience. As part of the study, fragility curves are being developed to consider extreme wind loads on electrical pylons.

Table 5 presents a cross-walk between the wind damage information in each of the wind models and DoD RPAD. The HAZUS model cross-walk was conducted at the Tier 3 level and the Florida model was cross-walked at the Tier 2 scale due to insufficient available information. The table uses the categories as presented in Table 2, above. In general, the table reflects the fact that the HAZUS model only covers the general building stock categories.

Table 5. Coverage of DoD facility class assets in the reviewed wind impact models. Indicating coverage of DoD assets (Tier 3 RPCS asset level) and by the wind impact models. Results are aggregated to RPCS Tier 1 level (e.g., "Operations and Training"). Grey shading indicates 'no coverage';; orange shading indicates there is only "low coverage" with less than one-third of Tier 3 assets represented for a respective Tier 1 category; light red shading indicates 'medium coverage' with less than two-thirds; and red shading indicates 'high coverage' with more than two-thirds of Tier 3 assets represented within the tier 1 category.

Wind Model	RPCS Classification Categories of Tier 1 Classification								
	Operation and Training	Maintenance and Production	Research, Development, Test, and Evaluation	Supply	Hospital and Medical	Administrative	Housing and Community	Utility and Ground Improvements	Land
HAZUS-MH (United States)									
Florida Public Hurricane Loss Projection model (Florida)									

2.2.2.5 Areas of Uncertainty

Uncertainties in wind modeling arise in part from incomplete scientific knowledge concerning hurricanes and their effects upon buildings and facilities. They also result from the lack of data, such as incomplete or inaccurate inventories of the built environment, and demographics. This lack of knowledge and information requires approximations and simplifications that are necessary for comprehensive analyses.

Modeling losses associated with high velocity winds is a complex and difficult undertaking that is wrought with uncertainties. Many of the uncertainties outlined above are relevant to the uncertainties associated with wind models, in addition (Pinelli et al., 2004):

- Fragility curves are location specific, and their development for a range of structures is time and computationally intensive. For the Florida model, fragility curves were developed based on a few structures that were chosen as being representative of a significant portion of the Florida

[14] Note that the UK Government/ Newcastle University is currently developing one such model called RESNET: Resilient Electricity Networks.

building stock. There is uncertainty involved in the extrapolation of these results to the entire building population.

- Some critical issues regarding cost uncertainties include estimations of repair costs, due to uncertainties in the correspondence between actual physical damage and cost projection. For example, if a window is damaged, a repair of the wall might include the removal and replacement of the openings, or the entire wall and shingles might have to be replaced for the sake of consistency and aesthetic appearance.
- Engineering simulations to build the fragility curves in the Florida model only included the structural elements, and did not include the damage to mechanical, electrical, plumbing, and kitchen installations as well as the damage to internal partitions and other element.
- Because assessment of damage to contents is highly dependent on the rain intensity of the hurricane and the fact that a house might experience leaks even without envelope breach, estimate of contents damage also involves a lot of uncertainty.
- Another primary source of uncertainty pertains to the building properties assumed, including the strength of components, the variability of construction techniques and quality, materials used, effects of aging, load path assumptions, and other considerations.
- A considerable contributor to uncertainty is inherent in the relation between a given wind speed and resultant forces in the building envelope. Wind tunnel data are available to define these coefficients more realistically for only a small handful of structural shapes.
- The estimates of the wind speed itself involve a significant degree of uncertainty that affects the final damage estimate. An additional uncertainty associated with wind models is that 'gust speed' data prior to 1990 is considered uncertain.
- Although the HAZUS Model can be used to estimate losses for an individual building, the results must be considered as average for a group of similar buildings. It is frequently noted that nominally similar buildings have experienced vastly different damage and losses during a hurricane.
- The HAZUS model contains definitions and assumptions regarding building strengths that represent a norm for construction in hurricane zones. These norms are defined in the technical manual. Where construction quality is known to be different from the defined norms, larger uncertainties in loss projections may be realized.

Similar to uncertainties associated with the flood impacts models, basic lack of data and information, as well as underlying knowledge deficiencies combine to create uncertainty. Improved data collection on the assets at risk, and on historical wind events and damages can help to reduce some of the underlying data uncertainties. In instances where risk and consequence (e.g., losses) are perceived to be high, data collection on critical assets or systems (properties, locational risks, etc) can reduce underlying uncertainties. To consider uncertain projected future changes in hurricane frequency and intensity, different techniques can be employed, including scenario analysis, Monte Carlo assessment, and Bayesian methods.

2.3 Studies Assessing Economic Losses of Infrastructure Assets Due to Climate Stressors

Several studies were identified that quantified infrastructure damages associated with climate-related hazards, including landslides, changes in temperature, rainfall and flooding, snow loads, temperature extremes, permafrost, and freeze-thaw cycles. These studies include some damage information. A few illustrative studies are shown below to provide a sense of the types of hazards and impacts that are represented in these models.

2.3.1 Temperature, Rainfall, and Flooding Thresholds

To quantitatively assess climate change's consequences, Arndt et al. (2011) constructed a climate-infrastructure model based on stressor-response relationships and linked this to a recursive dynamic economy-wide model to estimate and compare road damages. The framework is applied to Mozambique under four future climate scenario simulations. Road infrastructure costs are separated into new construction costs and maintenance costs. Separate stressor-response values for new construction costs from temperature and precipitation effects are derived for paved and unpaved roads.

2.3.2 Landslide Loss Model

Simmons (2013) estimates rainfall-triggered landslide losses using an econometric model. This is an econometric model based on past landslide events and the respective damages (property damages and casualty information). The damage function is a regression of damages against a vector of independent variables that includes the number of days of rain in the month preceding the event. The damages are not infrastructure specific. Indirect impacts are not assessed. It is an approach that could potentially be applied to assess the damages to military installations as a result of rainfall-triggered landslides, but it is not a ready-to use, publically available model.

2.3.3 Snow Load, Temperature Extremes and Permafrost Modeling

Larsen et al. (2008) used the Infrastructure Security and Energy Restoration (ISER) Comprehensive Infrastructure Climate Lifecycle Estimator (or ICICLE) model to estimate projected costs of climate change, including thawing permafrost, on infrastructure in Alaska. This study coupled projections of future climate with engineering 'rules of thumb" to estimate how thawing permafrost as well as increased flooding and coastal erosion may affect annualized replacement costs for nearly 16,000 structures. The model estimates how much climate change will add to future costs of public infrastructure in Alaska. Even though the infrastructure in the database has an estimated value of $40 billion today, the database undercounts and undervalues some types of infrastructure, especially defense facilities, as information about the extent and value of defense facilities is often suppressed for reasons of national security. A new SERDP project, RC-2435, will be investigating potential changes in snow loads in interior Alaska and how they affect roof designs.

2.4 Applicability of Damage and Fragility Information at Different Levels of Analysis

Five levels of vulnerability assessment were outlined in the introduction of this paper: 1) department-wide screening, 2) Service-level screening, 3) installation-level screening, 4) detailed assessment level, and 5) detailed engineering design and construction. The choice of the level of assessment is determined by the decisions that are being informed. The focus of this entire section is on damage and fragility information that can be used broadly to inform vulnerability assessments of military assets to climate-related hazard loads. The use of damage and fragility information at different assessment levels is dependent in part on the purpose of the assessment, as well as upon the availability, representativeness, and cost of obtaining the information.

The purpose of the assessment, including the types of decisions that are being informed, is the most critical driver for determining the level of the assessment, and the corresponding level of damage and

fragility information required (e.g., multi- or single installation, multi- or single hazard, replacement costs of assets or functional status of assets, etc.).

The availability of the fragility and damage information for a specific level of assessment could be a limiting factor, given that it is limited to specific assets, hazards, and damage metrics. For example, even though HAZUS includes a large library of damage functions covering a range of assets, hazard coverage is restricted to water and wind-related hazard loads. In addition, though many mission critical assets are covered in the HAZUS library, many other military specific assets may not be covered. Finally, the typical damage metric employed is associated with economic costs, which may be useful, but does not directly address the capability of installations to carry out their missions.

The representativeness of the fragility and damage information for a given level of assessment also varies. For example, the damage functions provided in HAZUS are meant to be nationally-representative of classes of structures in the United States, and they may be sufficient if one is conducting a large study involving a large number of such assets within the United States (e.g., at the installation level), but the applicability of that damage function to an individual structure is questionable. Other models apply to specific geographies and locations, only, and global coverage of the necessary damage and fragility information is not available.

Overcoming availability or representativeness constraints often requires either developing new information, or calibrating the available information to be representative of the specific context under study. Given that damage and fragility information does not typically transfer well to other locations, existing damage and fragility information often requires calibration and/or further development to fit the specific characteristics of assets at other locations, a relatively time intensive and expensive process. In the SERDP study at Norfolk Naval Base (Burks-Copes et al. 2014), existing HAZUS damage curves were further developed for some assets, and for other assets deemed mission critical (not covered by HAZUS) new fragility curves were developed with functionality explicitly considered.

Note that the developed fragility curves do not provide an engineering-grade analysis of structural fragility, and are not appropriate for the purposes of engineering design and construction. Additional analysis would be required to provide asset specific design criteria for improved resilience to hazard loads (for target reliability levels). In the course of this review, we did look into fragility curves that had been developed for engineering design. These are structure specific, costly to develop, and certainly not meant to be applied to families of structures in larger scale analysis.

2.5 Recommendations

Based on the above analysis, the following recommendations are provided to DOD:

New investments in damage and fragility information would benefit from a prioritization exercise of DoD vulnerability assessment needs cross-walked against the currently available damage and fragility information in order to identify the missing damage and fragility information that is most needed to support the range of assessment levels. Since existing damage and fragility information is not comprehensive across assets and hazards, DoD will likely need to make investments to develop the fragility or damage information required to support vulnerability analysis at different assessment levels.

As one moves from the Service-level screen to the detailed assessment level, the level of detail of the damage and fragility information should correspondingly increase. Prioritization will allow for some filtering of information requirements, which can cut down on cost and time requirements.

A systematic approach for monitoring and recording disaster losses and hazard events at military installations would provide DoD critical observations and inform future studies and decisions. Efforts to increase knowledge of the system response to climate hazards, including investments in weather, hydrologic monitoring, and impacts data, can provide critical information to decision makers given the uncertainty surrounding current impacts, and future climate variability and change. This information can be useful to developing more accurate damage and fragility functions for specific locations and assets.

Generalized fragility or damage curves should be developed for a core set of common mission critical assets for installations and Services. For more detailed analysis, tailored fragility or damage information could be developed for mission critical assets. For Service- or installation-level analysis, less detailed (highly aggregated) damage and fragility information may be adequate for identifying where there are significant vulnerabilities. Some of the assets may already be included in the HAZUS library, and require further tailoring to specific locations. On the other hand, for detailed vulnerability assessments, DOD should invest in highly detailed, asset specific damage and fragility information for mission critical assets with long lifetimes, to better determine mission vulnerability and to evaluate response options. At the installation or detailed assessment level, efforts have been made to develop location-specific damage and fragility information, a relatively expensive process, which may rely on modeling, ground analysis, and expert opinion.

At the department-wide screening level, and for some Service-level screening assessments, the use of damage and fragility information may not be appropriate, and alternative approaches should be considered. Although coarse or highly aggregated damage information may be applied at large scales to provide an overall picture of loss, it will often result in significant inaccuracies at the scale of individual assets that can provide misleading results. At department-wide or Service levels, there is typically a large degree of heterogeneity in terms of geography, mission critical assets, and the types of hazards and hazard loads. Alternative screening methods—for example, a focus on exposure (e.g., overlaying hazard and asset information) rather than on sensitivity (as in the use of damage and fragility modeling)—can be a cost effective way to initially screen for vulnerability. An even less costly approach could be to rely heavily on expert knowledge to provide an initial indication of installations at risk now and in the future.

Service-level vulnerability assessments in areas facing similar hazards and with similar geographies, provide potentially good opportunities to use aggregate damage information (including from the HAZUS library). For example, a comparison of the relative vulnerability of coastal installation asset types to sea level rise and storm surge provides one such opportunity.

Despite limitations, the HAZUS flood and wind models currently provide the most comprehensive set of damage and fragility information for DoD purposes, and the application of this information is particularly appropriate for use in installation level assessments. At more detailed assessment levels, HAZUS information can provide a useful starting point for development of more tailored damage

information. The HAZUS flood model provides the best coverage of military assets of any of the reviewed models, though flood damage information for the following military assets is not available: training facilities, armories, supply facilities (e.g., liquid storage, cold storage), and waterfront infrastructure (e.g., pier). Depending upon the purpose, these may represent high value assets in terms of mission criticality or monetary value. Assessments at geographically smaller installations or at detailed scales within an installation require an understanding of individual asset values and characteristics that is not included in the HAZUS flood model library of curves, though these curves can provide a useful starting point for further calibration to specific contexts. The HAZUS wind model is relatively limited in terms of asset coverage, but still provides coverage of many building types.

3.0 Assessment of Data Quality in the Context of Conducting Vulnerability and Impact Assessments

3.1 Purpose and Scope of Data Quality Assessment

The purpose of this portion of the review was to provide an assessment of the quality of data necessary for climate impact or vulnerability assessment. Reliable and defensible analyses depend on data that are reputable, of good quality, and accessible to DoD. We supply an overview of types of environmental information that may be used in assessments and focus the analysis of data quality on topographic, bathymetric, and asset data relevant to military installations, especially coastal locations. We define data quality here to mean attributes of the data that can affect their utility, such as the accuracy, resolution, reference datum, spatial and temporal extent and coverage, metadata, frequency of collection, and model-related error. Each of these aspects of data quality is discussed in detail below. The end of this section also includes a summary for aligning data quality with the analytical hierarchy presented in Section 1.2.

Section 3 includes an assessment of data quality at a sample of DoD sites. A sampling approach is taken because the large number of DoD sites worldwide (> 5,000) precludes an assessment of data quality at each site. This section is focused on current or historical conditions and is not designed to assess information about the future, including future sea level rise or climate conditions. With a focus on data quality, this section does not provide any assessment of impact or vulnerability for DoD installations, and discussions of data quality do not address the quality of weather, climate, or hydrology information.

Although it was beyond the scope of this study to assess the data quality in every DoD site location, we did aim to capture likely variation in data quality and availability from site to site. Therefore, we employed a sampling approach to inform the available data and data quality across as broad a geographic distribution as possible and for multiple DoD Service branches. We selected five installations from the contiguous US (CONUS), one site from Alaska, and one site from Hawai’i. In the selection of installations, we also took advantage of the information and insight generated through previous SERDP reports and the sites studied. We sampled from the South Atlantic coast (Eglin Air Force Base and Naval Station Norfolk), the Pacific coast of CONUS (Naval Base Coronado, Joint Base Lewis-McChord), the Pacific coast off of Alaska (Joint Base Elmendorf-Richardson), Hawai’i (Joint Base Pearl Harbor Hickman), and the West South Central Region on the Gulf of Mexico (Naval Air Station Corpus Christi). We also briefly explored the possible variation in data quality and availability in overseas installations (Naval Air Station Sigonella and Marine Corps Air Station Futenma) (see Table 6 for the full list of sampled installations).

Table 6. Domestic and overseas installations sampled in this study.

Name	State or Country	Region	Military Service
Eglin Air Force Base	Florida	South Atlantic	Air Force
Naval Station Norfolk	Virginia	Mid Atlantic	Navy
Naval Base Coronado	California	US Pacific Coast	Navy
Joint Base Elmendorf - Richardson	Alaska	North Pacific	Air Force
Naval Air Station Corpus Christi	Texas	South Central US	Navy
Joint Base Lewis - McChord	Washington	US Pacific Coast	Army
Joint Base Pearl Harbor - Hickam	Hawaii	Central Pacific	Navy
Naval Air Station Sigonella	Italy	Central Mediterranean Coast	Navy
Marine Corps Air Station Futenma	Japan	Southeast Asia	Marine Corps

3.2 Related Environmental Data for Vulnerability and Impact Assessments

A variety of types of data are needed to analyze possible impacts and vulnerabilities to military functions and installations. As noted in the introduction, the decisions that an assessment is designed to inform and the decision-maker's tolerance for uncertainty in the findings drive the data requirements. This study focuses on topographic, bathymetric, and asset data, all of which are important for understanding potential impacts or vulnerabilities, particularly in coastal settings. The quality of those data types is addressed throughout subsequent sections. In addition to topographic, bathymetric, and asset data, there are a variety of other types of environmental data that are closely related and will be relevant for developing certain types of assessments, which are discussed in this section. These environmental variables, such as land cover, land use, hydrography, subsidence or uplift, shoreline position, slope, tide and water level, and the extent of wetlands can influence the interpretation of topography and bathymetry and the modeling of key impacts, such as storm surge. For example, storm surge run-up models that do not include local land cover will give less accurate results than those that do include these data. Table 7 provides examples and sources for datasets complementary to topographic, bathymetric, and asset data for impact and vulnerability assessment.

Table 7. Environmental data complementary to topographic, bathymetric, and asset data that are relevant to impact and vulnerability assessment.

Type	Example Source	Horizontal Resolution	Geographic Coverage	Last Update	URL
Coastal Land Cover	National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program Regional Land Cover	30 m (varies by location and date)	National coastline	1992, 1996, 2001, and 2006 (varies by location)	http://www.csc.noaa.gov/digitalcoast/data/ccapregional
Coastal Land Cover	NOAA Coastal Change Analysis Program High-Resolution Land Cover	1 m -5 m (varies by location)	Select watersheds in the Caribbean, the Pacific Islands region, and Monterey Bay, California	Varies by location	http://www.csc.noaa.gov/digitalcoast/data/ccaphighres
Land Cover	European Commission: Global Land Cover Dataset 2000	300 m	Global	2000	http://landcover.usgs.gov/glcc/
Land Cover	U.S. Geological Survey (USGS) National Land Cover Database 2011	30 m	National	2011	http://www.mrlc.gov/nlcd2011.php
Wetlands	National Wetlands Inventory	1:24,000	National	Varies by location	http://www.fws.gov/wetlands/index.html
Shoreline	NOAA	various	Global	February 2014	http://www.soest.hawaii.edu/pwessel/gshhg/
Aerial Imagery	Google Earth Pro	various	Global	Varies by location	http://www.google.com/enterprise/mapsearth/products/earthpro.html
Hydrography	National Hydrography Dataset and Watershed Boundary Dataset	1:24,000, 1:100,00, and 1:5000 (limited)	National	Varies by location	http://nhd.usgs.gov/
Land Subsidence	Subsidence Monitoring Network	<10 cm	Central California	NA	http://ca.water.usgs.gov/projects/central-valley/land-subsidence-monitoring-network.html

Type	Example Source	Horizontal Resolution	Geographic Coverage	Last Update	URL
Reference Tide and Water Level	NOAA National Water Level Observation Network	NA	US and territories	NA	http://tidesandcurrents.noaa.gov/nwlon.html
Sea Level	Permanent Service for Mean Sea Level	NA	Global	Ongoing monthly	http://www.psmsl.org

In assessing impacts or vulnerability to coastal installations, especially in an installation-level or detailed assessment, tide gauge and water level data are important for improved accuracy of sea level-related analyses (see Box 2). The National Water Level Observation Network (NWLON) is a permanent observing system managed by the NOAA Center for Operational Oceanographic Products and Services (CO-OPS). The NWLON is a network of 210 long-term, continuously operating water level stations throughout the US and its territories. In addition to water levels, the NWLON data-collection platforms also measure other oceanographic parameters including meteorological parameters. The NWLON provides the national standards for tide and water level reference datums used for a variety of applications including nautical charting and coastal engineering.[15] The NWLON data have a target vertical accuracy of 0.036 m (root-mean-square-error, 95% CI) (NOAA 2014). The online map interface (see Figure 5) provides access to information on current water levels as well as the local tidal datum.

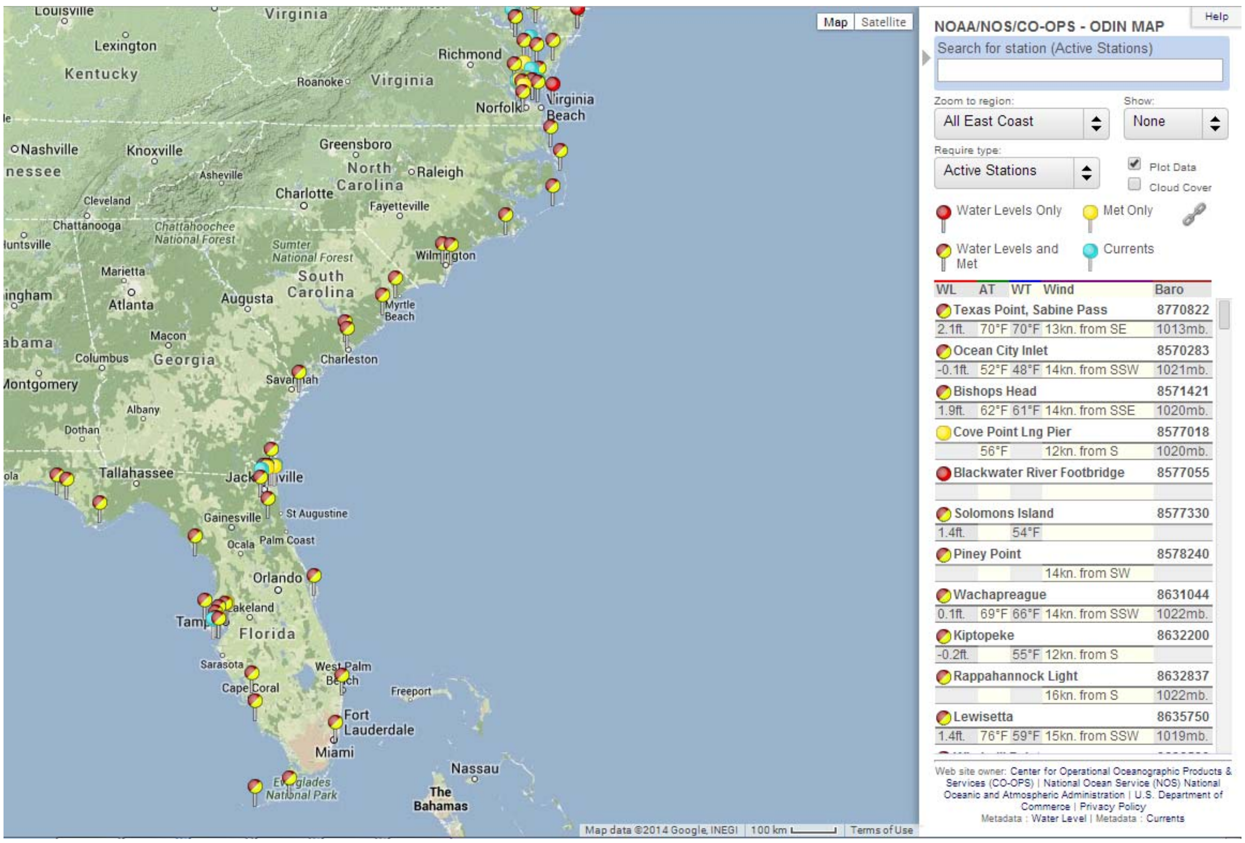

Figure 5. Example of available tidal observation stations through the National Water Level Observing Network. Center for Operational Oceanographic Products & Services (CO-OPS); National Ocean Service (NOS) National Oceanic and Atmospheric Administration; U.S. Department of Commerce; http://tidesandcurrents.noaa.gov/map/.

[15] (http://tidesandcurrents.noaa.gov/nwlon.html)

Box 2. Tide Gauge Temporal and Spatial Records

For tide gauge data, it is important to consider the length of tide station record required to obtain a robust estimate of the historic relative mean sea level change. Inter-annual, decadal, and multi-decadal variations in sea level are large enough that errors in sea level trends can result from using periods of record that are too short. The USACE advises that a tidal record should be at least two tidal epochs in duration (about 40 years) before being used to estimate a local MSL trend (USACE, 2011); the current 19-year reference period used by NOAA is the 1983-2001 National Tidal Datum Epoch.

The USACE recommends that if estimates based on records of less than 40 years are the only option, then the local trends must be viewed in a regional context, considering trends from simultaneous time periods from nearby stations (with records greater than 40 years) to ensure regional correlation and to minimize anomalous estimates (USACE, 2011)

The Permanent Service for Mean Sea Level (PSMSL) is a component of the UK Natural Environment Research Council's Proudman Oceanographic Laboratory, that has been collecting, sea level data since 1933 from the global network of tide stations. Global sea level data can be obtained from PSMSL via their web site (http://www.psml.org). The USACE recommends PSMSL as a source of information for stations not contained in the NOAA materials (USACE, 2011). However, caution is needed as not all of the PSMSL gauges have sufficient length of record for sea level analysis. PSMSL data vertical accuracy varies by location; many tide gauge instruments achieve 0.01 m or better vertical accuracy (Intergovernmental Oceanographic Commission of UNESCO 2006).

According to the USACE, there is good spatial coverage of tide stations along the US Atlantic and Gulf of Mexico coastlines, based on spatial density and record duration (USACE, 2011), which could support impact or vulnerability assessments of various levels of detail, provided proper care is taken in translation to local conditions and recording sources of uncertainty. Areas of the coastlines between Mobile, Alabama and Grand Isle, Louisiana, and in Pamlico/Albemarle Sounds, North Carolina contain no acceptable long-term tide-gauge records (USACE, 2011). For installations where there is a distant tidal station with a long historic data record and a close tidal station with a short historic record, especially for detailed assessments, a tidal hydrodynamics expert should be consulted as to the appropriate use of the closer tidal station data (USACE, 2011).

Land subsidence can influence the interpretation of topography or bathymetry in a location, affecting results from sea level rise and storm surge impacts modeling, which may be significant for impact and vulnerability analysis that require greater certainty to support decisions. The greatest rates of land subsidence in the US are caused by human activities, such as groundwater withdrawal or petroleum extraction (USGS, 1999). Land subsidence can also contribute to the relative sea level rise in a local area.

Tidal-station measurements of sea levels do not distinguish between water that is rising and land that is sinking; the combined elevation change of water rising and land sinking is referred to as relative sea level rise (USGS, 2013). Global sea level rise and land subsidence may increase the risk of coastal flooding and contribute to shoreline retreat in some coastal locations (see Figure 6).

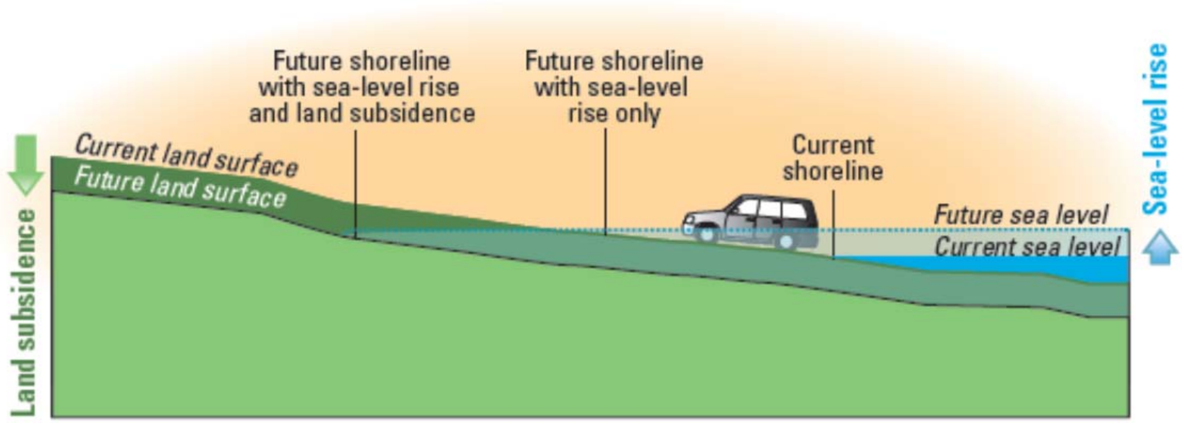

Figure 6. Influence of land subsidence and sea level rise on shoreline retreat. USGS 2013.

Land subsidence can also increase flooding in areas away from the coast where low-lying areas can be subject to increased flooding as the land sinks. Land subsidence may alter the topographic gradient that drives the flow of rivers and possibly contributes to more frequent or intense flooding (USGS, 2013). Land subsidence can be measured through a variety of methods including borehole extensometers, tidal station records, geodetic surveys (multiple or continuous; optical leveling or GPS), and remotely sensed Interferometric Synthetic Aperture Radar (USGS, 2013), and the vertical accuracy of the measurements varies by technique and location.

Uplift may influence local topography or bathymetry in a location over time, with the most common cause due to glacial isostatic rebound or tectonic driven uplift. Model correction for these common sources can be incorporated into tide gauge records (NRC, 2012), though uncertainty in measurement may be introduced through these corrections and may need to be considered in detailed assessments.

Land cover plays an important role in impact and vulnerability assessment modeling, especially in storm surge numerical models. Land cover has an impact on the forcing (changes in wind momentum transfer to water column) and dissipation (bottom friction) mechanisms of storm surge (Ferriera et al., 2014). Land cover data are available from several sources, including the Coastal Change Analysis Program (30 m resolution; NOAA Coastal Services Center), the National Land Cover Dataset (30 m resolution; USGS); and the Gap Analysis Program (30 m Resolution; USGS). In addition, coastal wetlands can mediate the impacts of sea level rise and storm surge to coastal assets. They are also a dynamic ecosystem, which may change in structure and function over time, especially in areas experiencing local sea level rise. The National Wetlands Inventory (NWI) contains data on the extent of wetlands (and inland deep water habitats) that have been determined from remotely sensed data, as well as digitized 1:24,000 scale hardcopy wetlands maps. Differences between classifications in land cover data sets result in different friction parameter inputs to storm surge modeling (i.e., ADCIRC) that have been shown to impact results

of storm surge modeling by approximately 7 percent of the surge height (Ferriera et al., 2014), and are therefore an important source of uncertainty in analysis with low tolerance, such as detailed assessments.

3.3 Data Quality Characteristics

Data quality is a general term that we use here to refer to a set of data characteristics that are important to consider in the application of data for impact or vulnerability assessment. In this section, we discuss the key data characteristics that inform an understanding of data quality and the alignment of data to application and decisions as a component of their quality.

3.3.1 Metadata

Metadata are necessary for quality control of the data used in an assessment, aligning or coordinating across datasets, and communicating results effectively for replication. Metadata provide information about the data contained in a dataset, including the content, known errors, type, creation, and spatial information. Metadata are critical for integrating data from multiple sources, especially for aligning data sources in a continuous manner necessary for coverage across the extent of analysis. Properly maintained metadata also helps to ensures the proper continuity for further analysis by others parties. For topographic and bathymetric data (and some types of asset data) the characterization of spatial and temporal resolution is critical for vulnerability assessments.

The Federal Geographic Data Committee (FGDC) is an interagency committee that, “promotes the coordinated development, use, sharing, and dissemination of geospatial data on a national basis” (http://www.fgdc.gov/). The National Spatial Data Infrastructure (NSDI) is a network designed to enable sharing of the nation’s geographic information digital resources. In general, federal organizations and stakeholders in the NSDI network utilize the Content Standard for Digital Geospatial Metadata (CSDGM), Version 2 (FGDC-STD-001-1998), which is the current Federal metadata standard. All federal agencies have been required to use this standard to document geospatial data created since January 1995. Currently, ISO standard 19115 and associated standards (the ISO suite of geospatial metadata standards referred to as 191**) have been endorsed by the FGDC and federal agencies are encouraged to transition to these ISO standards.[16]

3.3.2 Vertical Accuracy and Horizontal Resolution

The vertical accuracy of topographic and bathymetric data (discussed in detail in Section 3.4) is an important determinant of data quality for impact and vulnerability assessments. Accuracy of data refers to the degree to which information matches true values or has measurement error (JCGM, 2008). Vertical accuracy has a large influence on delineating inundation zones in impact modeling (Zhang, 2011; Murdukhayeva et al., 2013). To properly represent the uncertainty in potential inundation levels, absolute vertical accuracy of elevational data must be known (Gesch, 2009). Generally, root-mean-square error (RMSE) is used to estimate vertical positional accuracy, as recommended by the National Standard for Spatial Data Accuracy. Understanding the level of accuracy is critical for determining

[16] More information on transitioning to ISO 19115 standard can be found at: http://www.fgdc.gov/metadata/geospatial-metadata-standards.

whether data are appropriate for the assessment being conducted. For example, if the vertical RMSE of certain topographic data is greater than the change in sea level or storm surge being considered, those topographic data will not be appropriate (Gesch, 2009), even if the horizontal resolution of the data appears to be high quality (see Figure 7).

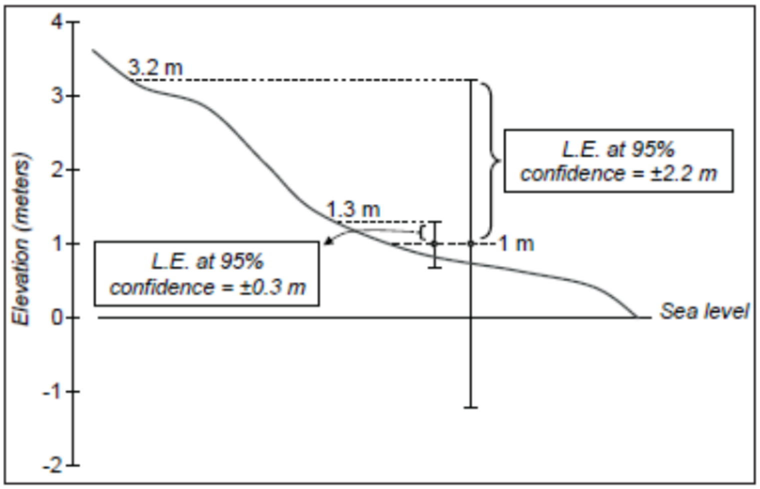

Figure 7. Diagram of hypothetical sea level rise mapped with two elevation models with differing vertical accuracy. Gesch, 2009.

In datasets that report RMSE for vertical accuracy, it is important to remember that these RMSE values are often reported as a single value for an entire dataset, though there may be geographic variation in vertical error. For installation-level assessments, which may utilize Lidar data for the entire region of interest, users may have greater tolerance for uncertainty and this level of reporting is sufficient (see also Box 3 below). In detailed assessments that require very high vertical accuracy, it will be necessary to validate the vertical RMSE using ground control points of high quality and accuracy (<2 cm) collected using survey-grade Global Positioning System (GPS) (Murdukhayeva et al., 2013). Real Time Kinematic (RTK) GPS may provide a way to address elevation uncertainty issues in sea level rise inundation risk assessments. RTK GPS protocols, however, require that a GPS base station be operated at a location that has been surveyed to within a few millimeters. Therefore, a network of accurate geodetic control sites within 5 km is needed for RTK GPS measurement at sentinel sites (Murdukhayeva et al., 2013).

Data resolution refers to the smallest detectable increment that an instrument, or the resultant dataset, can display. For geospatial datasets, horizontal resolution, also referred to as nominal post spacing, is the "smallest distance between two discrete points that can be explicitly represented in a gridded elevation dataset".[17] In many cases, this resolution is reported as "grid spacing", "cell size", or "grid size." For example, the National Elevation Dataset (NED) is available in certain parts of the US at 1 arc-second resolution (about 30 meters), indicating a grid with each cell approximately 30 meters on a side, and it is available in other locations at 1/9 arc-second, equivalent to a grid with each cell approximately

[17] http://www.ndep.gov/glossary.html

3 meters on a side. Any point within a grid cell, at whatever resolution, will have the same value as all other points within that cell.

Higher resolution data reduces the uncertainty in the results of an impact or vulnerability assessment. For example, with topographic data at 30 meter resolution an assessment may be able to determine whether any part of an installation will be exposed to future impacts, but it will not be able to distinguish between the level of impact on two buildings that are 10 meters apart within that installation—the decision context and tolerance for uncertainty will dictate whether this is acceptable quality. Accurate delineations are especially important if the potential inundation area is used subsequently to generate estimates of affected population, land cover types, infrastructure, or economic activity (Gesch, 2009).

Data precision refers to the level of measurement reproducibility in the dataset. As with all data, more precise data do not necessarily mean more accurate data. A precision index may be used to demonstrate the dispersal of errors about a mean of zero and to show the error at different probabilities (Greenwalt and Shultz, 1962) for different sources of cartographic data.

3.3.3 Datum

Datums provide reference base elevation to reckon heights or depths. For impact and vulnerability assessments, the datum defines base elevation to be used across relevant datasets, such as topography, bathymetry, sea level, or asset elevation. Using a consistent datum or converting to a common datum is important for comparing heights or depths across these types of data and consistently comparing data across regions.

North American Vertical Datum of 1988 (NAVD88) is now the reference vertical datum in the United States. The vertical error of NAVD88 nationwide is approximately 5 cm (Zilkoski et al., 1992), which does not include any systematic errors such as untracked subsidence. The NAVD88 is an orthometric datum (i.e. based on a mean sea level height), based on the Helmert Orthometric Height, which uses a primary tidal benchmark at one location (Rimouski, Quebec, Canada).[18] In the United States, the standard horizontal datum is the North American Datum 83 (NAD83). The NAD83 is a surface defined by an ellipsoid (Geodetic Reference System 80) with origin at the Earth's mass center and measurements are accurate to about 2 cm nationally (Zilkoski et al., 1997). World Geodetic System 84 (WGS 84) is the commonly used datum for global datasets.

Tidal datums are used as references to measure local water levels. Tidal datums include Local Mean Sea Level, Mean Lower Low Water, Mean Low Water, Mean High Water, Mean Higher High Water, Mean Tide Level, and Diurnal Tide Level. Mean Lower Low Water is the reference datum for predictions, bench mark publication and nautical charts. Tidal datums are local vertical datums that may change considerably within a geographical area (NOAA 2003b). Bench marks are used to reference local tidal datums to fixed points. The NOAA National Geodetic Survey (NGS) maintains a National Spatial

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[18] See http://www.nauticalcharts.noaa.gov/csdl/learn_datum.html for more information.

Reference System (NSRS) that can be connected to the tidal bench mark to establish the relationships between tidal datums and a geodetic datum.[19]

Uncertainty introduced through datum transformation can affect data quality for impact of vulnerability analysis. The NGS and the USACE have each developed freely available software to aid the conversion from a local measurement reference system to a national datum, as well as between national datums.[20] NOAA National Ocean Service and NGS developed a vertical datum transformation tool, VDatum for the conterminous USA to transform elevation data among approximately 30 vertical reference systems within the three major classes: tidal datum, orthometric datum, and 3-dimensional or ellipsoid datum (Parker, 2002). The VDatum website has an excellent discussion of issues related to datum transformation, accuracy of transformation, and accuracy of source data.[21] For datum corrections related to sea level rise analysis, through support from SERDP Flick et al. (2012) have augmented the guidance from the USACE (USACE, 2011) for estimating local mean sea level rise from global scenarios of sea level rise. It is important to note that in datum transformation, as much as 20 cm of vertical error may be introduced[22], which would have a significant effect on detailed and installation-level screening impact and vulnerability assessments.

3.3.4 Geographic Coverage and Data Continuity

The geographic extent of coverage for a particular data source can influence data quality. For example, when analyzing multiple locations, such as in a Service-wide assessment, the geographic extent of coverage and comparability of data are paramount. In addition, because different data sources have different spatial coverage, such as high-resolution Lidar data at particular coastal locations from multiple sources or flight missions, issues may arise in creating seamless coverage for the location of interest, causing gaps in analysis.

Techniques for aligning data from different sources, or edge matching, are common in geographic information system (GIS) analysis today. In situations where there are gaps in coverage, there are several options to improve coverage, though there is no substitute for complete data. In some situations it may be appropriate to interpolate between existing data points for the gap area, but whether this is appropriate will depend on the level of uncertainty that can be accepted in the analysis. Moving to a lower resolution will provide greater coverage, with the obvious loss of certainty for analysis.

3.3.5 Frequency of Collection or Updating

The frequency with which data are collected or updated can have an impact on data quality. For example, natural processes or anthropogenic influences, such as dredging or dumping may lead to changes in bathymetry over time. Data collected at more frequent intervals will allow for more detailed analysis, especially in highly dynamic systems like shorelines, where seasonal shifts in shoreline or major

[19] See http://tidesandcurrents.noaa.gov/datum_options.html for more information on tidal datums.
[20] The USACE CORPSCON software can be downloaded at www.tec.army.mil; NOAA NOS and NGS developed VDatum at http://vdatum.noaa.gov.
[21] http://vdatum.noaa.gov/docs/est_uncertainties.html
[22] See http://vdatum.noaa.gov/docs/est_uncertainties.html for examples across several US regions.

storm events may be significant. In addition, anthropogenic or natural uplift or subsidence can affect the topography over time. Asset data may be supplied based on the condition of the asset at the time it was built. Therefore, asset data that capture more up-to-date conditions (including deterioration over time or upgrades) may be more accurate and useful, especially for installation-level screening or detailed assessments. Gaps in data due to infrequent collection or lack of historical data may also affect the ability to establish important baseline metrics, as for example in establishing the sea level mean and/or trend from tide gauge records. In general, recent or frequent sampling of these data types can greatly improve data quality.

Challenges related to frequency of collection can sometimes be overcome by combining multiple data sources to span data gaps or corroborate between datasets. Service data sources such as Geobase (Air Force) and NGEMS (Navy) may address in part some of the issues regarding update frequency. Interpolation between records may also be possible. Nevertheless, like strategies to address spatial gaps in data coverage, methods used for addressing temporal gaps should be viewed with caution, especially where decisions have a low tolerance for uncertainty, as error will be introduced.

3.3.6 Model Inputs and Model Output Data

Data quality can be affected by error introduced through model processing steps. In particular, error is introduced when bathymetric and topographic data are interpolated into grids suitable for numerical modeling such as to simulate river flooding, sediment dynamics, and storm surge (e.g., Digital Elevation Models (DEMs) and the Triangular Irregular Networks (TINs) used in ADCIRC modeling). This source of error is often not well characterized, but may impact the quality of the data for assessment purposes and should be specified in all final products. When converting photogrammetric or Lidar-generated data to a TIN or DEM contours, existing techniques should be used to keep error introduced during the conversion to a minimum; nevertheless, some degree of error will be introduced because the areas in the grid that are distant from actual observations are only an approximation (NDEP, 2004). Derivatives of the TIN may exhibit even greater error, especially when generalization or surface smoothing has been applied to the final product (NDEP, 2004). Interpolation error introduced in developing DEMs from trackline or multibeam sonar bathymetry should be noted and may impact utility of data in detailed assessments.

3.4 Topographic, Bathymetric and Asset Data

Impact and vulnerability assessments that are designed to inform decision across levels of analysis, from Service-level screening to detail assessment (see section 1.2), often use topographic, bathymetric, and asset data. In this section we discuss the quality of available topographic, bathymetric, and asset data for assessments at military installations, as well as barriers to use of the data and opportunities to overcome those barriers. We use a sample of military installations to better understand the potential differences in data quality across DoD installation locations and assets.

3.4.1 Topographic Data

Topographic data sets provide information about the elevation of the surface of the Earth. The measurement and representation of topography, usually in the form of DEMs, are needed to understand

the potential impacts and vulnerabilities from a variety of climate related hazards including coastal flooding from sea level rise and storm surge, as well as riverine flooding in coastal or upland areas, because damage is commonly related to depth of flooding. Topographic data are often inputs to impact models. The horizontal resolution and vertical uncertainty in these data affect the amount of uncertainty regarding these impacts related to the ground elevation of the system being analyzed.

Topographic data are acquired at a variety of resolutions (see Table 8). Remote sensing technology, primarily Lidar and IfSAR (Interferometry Synthetic Aperture Radar; also known as InSAR) provide data at high resolutions (<1 m) (see Box 3). Data at lower resolutions (>1 m and often >10 m) are generally acquired through cartographic contours, for example in the underlying topographic data for the NED 10-meter DEM.

RTK GPS data are not widely available. Some states do maintain base stations, which can be used for referencing collection of new data. Nevertheless, no public sources relevant to military installations were located in our review. These data are collected as part of modern surveys and installations may have some site-specific data. If decisions supported by detailed assessment require vertical accuracy of <10 cm, collection of new RTK GPS may be necessary.

Table 8. Common types of acquisition of topographic data and associated vertical accuracy, horizontal resolution and coverage. Values are representative and actual vertical accuracy and horizontal resolution will vary by actual collection instrument and conditions.

Data Type	Vertical Accuracy	Horizontal Resolution	Coverage
Lidar	15 cm	1 m or greater	Partial National, especially coastlines
IfSAR (Interferometric Synthetic Aperture Radar)	0.1 m-1 m	1 m or greater	Partial or full coastal counties in FL, MS,AL, CA, and HI; location specific
Shuttle Radar Topography Mission (SRTM)	16 m (90%CI)	1-arc second (~30 m)	All land area 60N to 56S
Photogrammetry (e.g. Leica Geosystems ADS40 airborne digital sensor)	0.5-2 m	2 m or greater	Location specific
Real-Time Kinematic GPS	<10 cm	<2 cm	Location specific

The US Interagency Elevation Inventory is a collaboration between NOAA and the USGS to provide a nation-wide, comprehensive listing of high-accuracy topographic and bathymetric data.[23] National coverage of topographic data is available through the NED 10 m DEM, and Lidar and IfSAR data are available for certain portions of the United States (see Figure 8). In some areas, state and local GIS

[23] http://www.csc.noaa.gov/inventory/#app=b74d&bde-selectedIndex=1 and http://www.ngdc.noaa.gov/mgg/dem/demportal.html

Departments or data warehouses can provide topographic data specific to that location. The NGDC provides consistent publicly available 30 arc-second global data through the Global Land One-Kilometer Base Elevation Project (GLOBE).

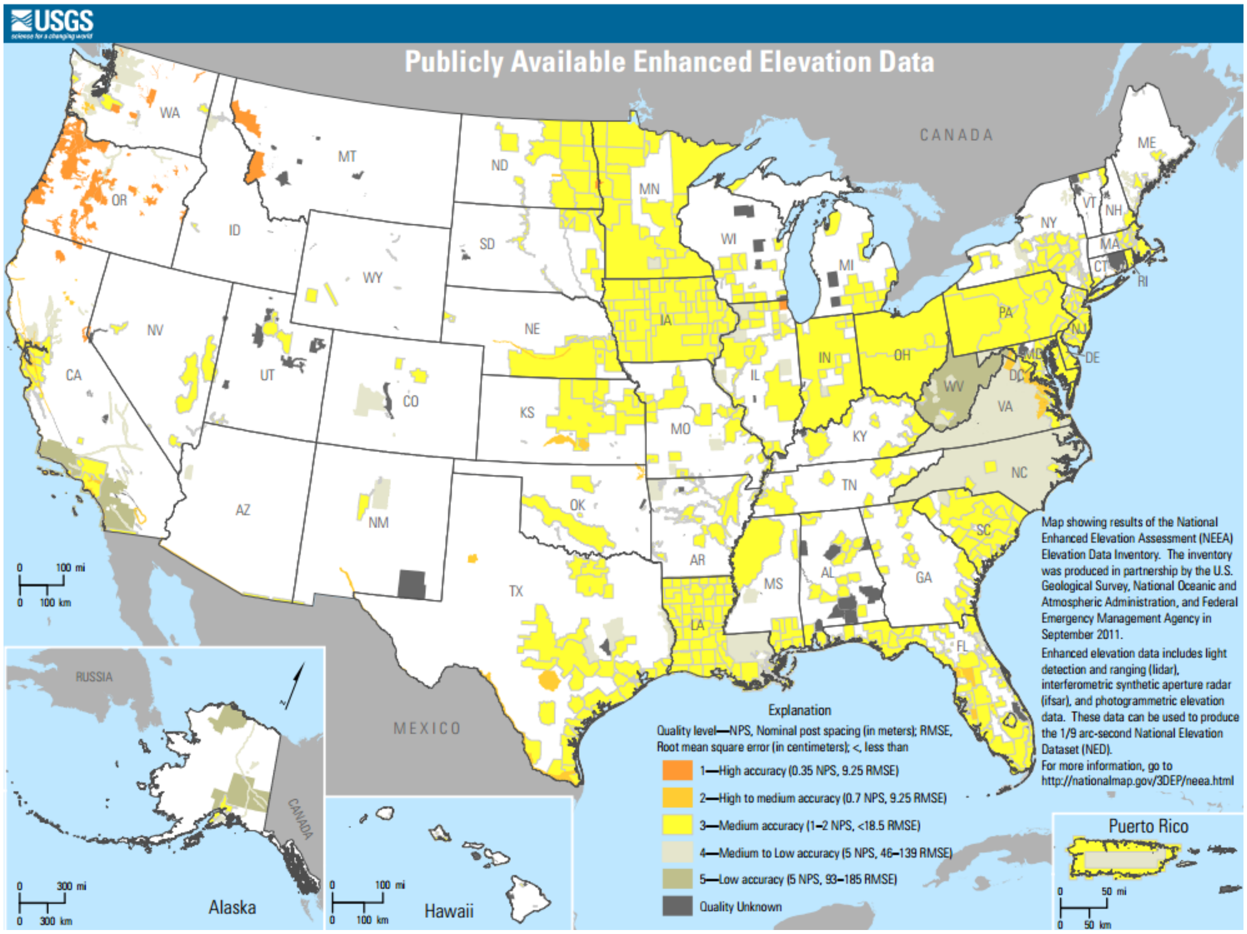

Figure 8. Map of elevation data publicly available through the National Elevation Dataset. Source: http://nationalmap.gov/3DEP/documents/enhanced_elevation_data.pdf

Topographic data were located for a selected list of domestic and international military installations with the intended purpose to provide a geographic overview of data quality and availability. Information on each topographic data source was obtained through online searches, governmental data clearinghouses, and academic journal reviews of sea level rise risk assessment studies. For some military instillation locations, additional high-resolution topographic data may be available from classified sources. However, the authors were unable to determine coverage or resolution details regarding such data. For each installation that we reviewed, one or more of the highest resolution, publicly-available data sources were included in our summary. For each dataset, we provide relevant information on data quality characteristics (see Table 9).

Box 3. Common Sources of Lidar Error

The improved vertical accuracy of Lidar elevation data relative to traditional USGS topographic maps, as well as its increased spatial resolution, provides enhanced topographic information that can improve impact and vulnerability studies. Nevertheless, there are several sources of error to consider when using Lidar data, especially for detailed assessments.

Data collection, terrain slope, land-cover type, Lidar sensor, and filtering methods can all contribute to vertical accuracy in Lidar data (Hodgson and Bresnahan, 2004; Shen and Toth, 2009). Sources of Lidar positional error (xyz) in data collection include the global positioning system (GPS) that records the aircraft's xyz position, the inertial measurement unit (IMU) for monitoring the aircraft's attitude (yaw, pitch, roll), and the ranging and direction of the laser beam (Hodgson and Bresnahan, 2004; Shen and Toth, 2009). Land-cover and terrain morphology also affect the performance of filtering methods used to classify Lidar 'ground' returns used to generate bare-earth DEMs (Aguilar et al., 2010).

The lack of a standard method of describing Lidar error leads to inconsistent and misleading reporting of uncertainty and error. Most commonly the RMSE linear error is applied as a single measure across the entire DEM. The major limitation is that it requires errors to follow a normal distribution with zero bias. However, Lidar errors are sometimes biased (Adams and Chandler, 2002; Aguilar and Mills, 2008; Hodgson et al., 2005). The Lidar elevation bias will further complicate the mapping applications because Lidar with a systematic positive bias will overestimate the land surface elevation (Kraus and Pfeifer, 1998; Schmid et al., 2011), thus underestimating potential inundation. Likewise, Lidar with a systematic negative bias will underestimate the land surface elevation (e.g. Adams and Chandler, 2002; Hodgson et al., 2005), thus overestimating potential inundation. Ground surveys can provide estimates of bias or error within Lidar data sets (see for example Bales et al. 2007), but it is unclear how often such techniques are employed as opposed to accepting reported error values.

Table 9. Publicly available topographic data for select military installations.

Base	Source	Data Type	Metadata Standard	Vertical Accuracy[24]	Vertical Datum	Horizontal Resolution	Horizontal Datum	Geographic Coverage	Last Update
Norfolk Naval Station, VA	NOAA	SRTM, Lidar	ISO	.15 m-7 m	MHW[25]	1/3 arc-second (10 m)	WGS84	VA Beach, NC, City of Norfolk, mouth of Chesapeake Bay and southern tip of Delmarva peninsula	Jan 2007
Eglin Air Force Base, FL	USACE National Coastal Mapping Program (JALBTCX)	Lidar	FGDC	18 cm RMSE	NAVD88	50 cm	NAD83	Alabama, Florida	2010
	FEMA FIRM[26]	Lidar	FGDC	7.6 cm RMSE	NAVD88	Not Reported	NAD83	Okaloosa County (coastal)	2007
	Northwest Florida Water Management District	Lidar	FGDC	15 cm	NAVD88	1 m	NAD83	Okaloosa County[27]	2008
Naval Base Coronado, CA	CA Coastal Conservancy	Lidar	FGDC	18 cm RMSE	NAVD88	1 m	NAD83	San Diego Bay	2009-2010
	Southern California Beach Process Study	Lidar	FGDC	Not Reported	NAVD88	Not Reported	WGS84	Southern California Coastline	2010
	USGS	Lidar	FGDC	10 cm-1 m	NAVD88	1 m-3 m	NAD83	Southern California	2009
Joint Base Elmendorf – Richardson, AK	National Elevational Dataset	SRTM	FGDC	Not Reported	NAVD88	10 m	NAD83	National (incl. Alaska)	2009

[24] The National Standard for Spatial Data Accuracy uses RMSE to estimate vertical accuracy, reported in ground distances at the 95% confidence level (Federal Geographic Data Committee, 1998), which is the assumed method unless otherwise noted in representative values, as not all sources report estimation technique.

[25] Mean High Water (MHW) is the average of all the high water heights observed over the National Tidal Datum Epoch (19 year period over which tidal data are analyzed) (http://tidesandcurrents.noaa.gov/).

[26] Federal Emergency Management Agency Flood Insurance Rate Maps (FEMA FIRM)

[27] Data for additional counties available through Northwest Florida Water Management District Lidar portal: http://www.nwfwmdlidar.com/.

Base	Source	Data Type	Metadata Standard	Vertical Accuracy[24]	Vertical Datum	Horizontal Resolution	Horizontal Datum	Geographic Coverage	Last Update
Naval Air Station Corpus Christi, TX	FEMA	Lidar	FGDC	9.7 cm RMSE	NAVD88	Not Reported	NAD83	Nueces County	2006
Joint Base Lewis – McChord, WA	Puget Sound Lidar Consortium	Lidar	FGDC	< 30 cm RMSE	NAVD88	2 m	NAD83	Puget Sound Lowlands	2002
Joint Base Pearl Harbor – Hickam, HI	FEMA	Lidar	FGDC	13.7 cm RMSE	Not Reported	Not Reported	NAD83	Mamala Bay (incl. Pearl Harbor)	2006
	NOAA CSC	Lidar	FGDC	8.2 cm RMSE	Local Tidal Datum	Not Reported	NAD83	Pearl Harbor	2005
Naval Air Station in Sigonella, Italy	European Commission Joint Research Centre (same as NASA SRTM)	SRTM	Other	16 m	Not Reported	3-arc seconds (~90 m)	WGS84	Global	Jan 2003
Marine Corps Air Station Futenma, Japan	NASA	Not Reported	FGDC or ISO	Not Reported	Not Reported	50 m	Not Reported	Japan	1984

In general, topographic data sampled at military installations adhere to internationally recognized metadata standards. Many of these data have been updated in the last decade. They also utilize well established datums, though there is some variability between locations based on the extent of dataset (i.e., local, regional, or global). The vertical resolution, vertical error, and horizontal resolution vary by collection method. The sample of military installations suggests the general availability of easily accessible Lidar based topographic data for coastal US locations, primarily through NED. Additional topographic data may be available from military Service sources, such as and the Army Geospatial Center or Marine Corps GeoFidelis, which are access-controlled and were not reviewed.

For locations outside of CONUS, including Alaska and international locations, readily available data are generally only found at a lower resolution, which may not be suitable for installation-level screening or detailed analyses. In those cases, additional data collection may be needed to support assessments where a high level of certainty is needed to support decision making. At international sites, where publicly available data are limited, national governments may have high resolution topographic data. However, these data are often difficult to obtain. In some instances, classified data at higher resolutions for domestic or international locations may exist. In areas adjacent to military installations, topographic data may not be available at the same resolution as for the installation, especially in international locations. This may impair certain types of analyses that require data continuity across installation boundaries. Options for collecting original data may be constrained by local agreements, such as limitations of collection of high-resolution data by the DoD in other countries.

3.4.2 Bathymetric Data

Bathymetric data provide information about the depth and shape of underwater terrain. Like topography, bathymetry influences and is influenced by coastal processes and is important for determining potential impacts and vulnerabilities. Bathymetric data, or digital elevation models created from bathymetric data, are used in storm surge modeling, and the quality of data will influence the uncertainty in projected impacts for an assessment.

Bathymetric data primarily come from SONAR (Sound and Navigation Ranging) or Lidar techniques, which are processed at various resolutions. The National Geophysical Data Center (NGDC) is the US national archive for a variety of bathymetric data, including National Ocean Service (NOS) Hydrographic Surveys, and non-NOS multibeam sonar and singlebeam sonar data. NOS Hydrographic Surveys are high resolution, shallow water data used to compile the official nautical charts for the United States and its territories. Modern multibeam instruments of higher quality than previous generations of equipment are used for recent NOS Hydrographic Surveys and must be approved as chart quality by the NOS Office of Coast Survey. These data are collected to International Hydrographic Organization (IHO) standards, which including the use of FGDC metadata standards.

In most cases, multibeam sonar data are used to derive digital elevation models that can be used for modeling analyses, such as storm surge modeling. These DEMs are of varying horizontal resolution, though for several coastal US regions, they are available at 1-arc second resolution or 3-arc second (~90

m) resolution. As noted above, the US Interagency Elevation Inventory provides a nation-wide, comprehensive listing of high-accuracy bathymetric data.[28] For comparable global data, the bathymetric DEMs are available at 30-arc seconds (~1 km).[29] The uncertainty introduced in creating the DEM will likely be important to results of detail assessments, as discussed in section 3.3.6. The vertical accuracy of bathymetric data is often not reported.

Alternative sources of bathymetric data include Coastal IfSAR (Interferometry Synthetic Aperture Radar) from NOAA, which provides 0.5 m to 1.0 m resolution coverage along the Gulf Coast region, coastal areas of northern and central California, and the eight major islands in Hawai'i. The USACE also maintains the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX), which maintains Lidar data from coastal areas of the United States under the National Coastal Mapping Program. International sources of bathymetric data include Japan's Global Oceanographic Data Center and the Mediterranean Science Commission, for those areas respectively. The NGDC also provides global bathymetric data at a 1-km resolution in the ETOPO1 global relief model.

Bathymetric data were located for a selected list of domestic and international military installations to provide a geographic overview of data quality and availability (see Table 10). We located information on each bathymetric data source through online searches, governmental data clearinghouses, SERDP studies, and academic journal reviews of sea level rise risk assessment studies.

[28] http://www.csc.noaa.gov/inventory/#app=b74d&bde-selectedIndex=1
[29] See for example, http://www.gebco.net/data_and_products/gridded_bathymetry_data/

Table 10. Publicly available bathymetry data for select military installations.

Base	Source	Metadata	Vertical Datum	Horizontal Datum	Geographic Coverage	Last Update (Previous)
Norfolk Naval Station, VA	NOS Hydrographic Survey F00583	ISO (Partially Complete)	MLLW	NAD83	Hampton Roads, Willoughby Bay, Lynnhaven Roads, Naval Amphibious Base Little Creek, Naval Station Norfolk	**2010** (1950, 1947, 1944, 1943, 1929)
Eglin Air Force Base, FL	USACE National Coastal Mapping Program (JALBTCX)	FGDC	NAVD88	NAD83	Alabama, Florida	2010
	NOS Hydrographic Survey H09995	ISO (Partially Complete)	MLLW	NAD1927	Fort McRee to Bayou Chico, Pensacola Bay	**1983** (1935 and 3 more Surveys)[30]
Naval Base Coronado	NOS Hydrographic Survey F00590	ISO (Partially Complete)	MLLW	NAD83	Entrance to San Diego Bay, Zuniga Point to Navy Pier	**2010** (1968 and 7 more Surveys)
	NOS Hydrographic Survey H08978	ISO (Partially Complete)	MLLW	NAD1927	Approaches to San Diego Bay	1968
Joint Base Elmendorf - Richardson	NOS Hydrographic Survey H11248	ISO (Partially Complete)	MLLW	NAD83	Cook Inlet, Fire Island Shoal to North Point Shoal	**2004** (1994, 1992, 1982, 1974, 1969, 1960, 1955, 1947, 1941, 1930, and 3 more Surveys)
	NOS Hydrographic Survey H10538	ISO (Partially Complete)	MLLW	NAD83	Cook Inlet, North Point to Point Mackenzie	1994
Naval Air Station Corpus Christi	NOS Hydrographic Survey H10365	ISO (Partially Complete)	MLLW	NAD83	Alongshore of the Encinal Peninsula	**1991** (1935 plus 1 unknown survey)
	NOS Hydrographic Survey H05694	ISO (Partially Complete)	Not Reported	Not Reported	Corpus Christi Bay	1935

[30] Surveys are listed in the NOAA viewer, however surveys are preceded with 'Unknown' rather than by a year (last update).

Base	Source	Metadata	Vertical Datum	Horizontal Datum	Geographic Coverage	Last Update (Previous)
Joint Base Lewis - McChord	NOS Hydrographic Survey H12050	ISO (Partially Complete)	MLLW	NAD83	Approaches to Puget Sound	**2009** (1936, 1935, plus 1 unknown survey)
	NOS Hydrographic Survey H12075	ISO (Partially Complete)	MLLW	NAD83	Southern Puget Sound, Eastern Nisqually Reach	2009
Joint Base Pearl Harbor - Hickam	NOS Hydrographic Survey H10124	ISO (Partially Complete)	MLLW	Old Hawaiian Datum	Offshore Diamond Head to Kaena Point	1984
	Main Hawaiian Islands Multibeam Bathymetry Synthesis	Not Reported	Not Reported	WGS84	Main Hawaiian Islands	2011
Naval Air Station in Sigonella, Italy	European Marine Observation and Data Network (EMODnet)	Common Data Index (CDI)	Not Reported	WGS84	Atlantic Ocean, North Sea, Western and Central Mediterranean, Iberian Coast, Aegean, Madeira	Varies
Marine Corps Air Station Futenma	British Ocenaographic Data Centre (BODC): GEBCO_08 Grid	Not Reported	MSL	WGS84	Not Reported	Varies

For the bathymetric data found at each of the sampled installation locations, review of the metadata revealed that though these metadata are provided in FGDC or ISO formats, the horizontal and vertical resolutions were often not included, particularly for the older survey records. NOS Hydrographic Surveys for 2010 in Norfolk Naval Station in Virginia and 2009 in Joint Base Elmendorf-Richardson in Puget Sound provided the most complete ISO standard metadata, which included vertical accuracy (expressed in units of meters for one standard deviation) and horizontal resolution. All metadata tables for the sources include information on geographic coverage, and description of the sounding vessel. Alongside the metadata, all sources obtained through NOAA's viewer included a descriptive report to complement the metadata.[31]

The sampled bathymetry data often report vertical and horizontal datums, though not in all instances. The NOS Hydrographic Surveys appear to regularly report this information. The frequency of collection varies both within and across data sources, and many of the bathymetry data are old enough that features may have changed so that data are no longer sufficiently accurate for detailed assessments. Changes in sonar equipment also affect the data quality, with more recent surveys generally considered more accurate. In terms of geographic coverage, there does appear to be extensive coverage of multibeam sonar collection, both in US coastal waters and globally, which is important for Service-wide screening assessments that require comparable data.

For installations within the United States, NOAA's NGDC provided the most continuous layer of both high and low quality bathymetric data. Although NOAA provides a comprehensive clearinghouse for the United States, international datasets may be obtained from the European Marine Observation and Data Network, the British Oceanographic Data Centre, and other national governmental agencies. Digital Nautical Charts[32] provided by National Geographic-Spatial Intelligence Agency (NGA) may provide additional information for international locations to support screening-level assessments; within the United States they are based on the NOAA data. In situations with a low tolerance for uncertainty, such as detailed assessments, new collection of bathymetric data may be necessary to provide high-resolution data of known horizontal accuracy and an up-to-date understanding of bathymetry.

3.4.3 Asset Data

Military assets relevant to impact and vulnerability assessments are real property, such as buildings, linear structures (e.g., pipelines, fences, power lines), and land. Information about the assets is critical for understanding impacts related to loss of facilities, as well as loss of function, which may be critical to mission continuity or success. Asset information is used in damage and fragility modeling as described in section 2.0. In this section we focus on the quality of available data for such analyses. The quality of asset data affects the uncertainty of modeling results and may determine whether certain models can

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[31] An example report for the area near Norfolk, VA can be viewed at: http://surveys.ngdc.noaa.gov/mgg/NOS/coast/F00001-F02000/F00583/DR/F00583.pdf

[32] https://www1.nga.mil/PRODUCTSSERVICES/NAUTICALHYDROGRAPHICBATHYMETRICPRODUCT/Pages/DigitalNauticalChart.aspx

be applied at all. For asset data, it is also important to understand how important an asset is to meeting the installations core functions, which at a screening level can help to prioritize resource intensive detailed assessments.

DoD is responsible for a wide variety of assets, from fence lines to hand grenade ranges and landing strips to barracks. DoD occupies over 290,000 buildings worldwide of more than 2.2 billion square feet and valued at over $567billion (DoD, 2013). Each of the 9 installations sampled for this review contain hundreds of owned buildings representing more than a million square feet at each location (see Table 11).

Table 11. Buildings owned and plant replacement value for select military installations. See source for standard calculation of Plant Replacement Value. Source: Department of Defense 2013.

Name	Buildings Owned		Plant Replacement Value ($M)
	Count	**Square Feet**	
Eglin Air Force Base	1652	11,182,384	3,921.0
Naval Station Norfolk	527	15,511,881	5,498.5
Naval Base Coronado	585	9,278,247	4,373.9
Joint Base Elmendorf - Richardson	410	8,175,070	4,567.6
Naval Air Station Corpus Christi	295	5,419,263	1,491.9
Joint Base Lewis - McChord	2085	24,009,787	12,272.5
Joint Base Pearl Harbor - Hickam	1045	15,458,490	13,941.5
Naval Air Station Sigonella (Italy)	157	1,578,793	838.8
Marine Corps Air Station Futenma (Japan)	224	1,087,793	977.6

Military Services in DoD each maintain their own asset databases. The Navy utilizes the Internet Naval Facilities Assets Data Store (iNFADS), which also includes information on some US Marine Corps assets. The Marine Corps also maintains GeoFidelis as a repository for geospatial and asset information. The Army has an Installation Geospatial Information and Services group and utilizes the Army Mapper Geospatial database (http://mapper.army.mil/) to manage and distribute asset information. The Air Force asset data are maintained in the US Air Force GeoBase system. The Builder Sustainment Management System may also provide additional information regarding asset condition or function, but was not included in this review.[33] Each of these systems includes a different set of asset characteristics specific to each military Service and access is restricted to authorized users, usually via Common Access Card credentials.

[33] http://sms.cecer.army.mil/SitePages/BUILDER.aspx

At the department level, data for military assets are compiled in the RPAD for all branches of the military by Defense Installations Spatial Data Infrastructure (DISDI). This information is the best available, asset information, including buildings (owned and leased), linear structures, and land, that is consistent across all military branches. The RPAD is populated from the Service-specific databases. However, it does not include all of the information from the Service-specific systems. A complete list of asset attributes compiled in the RPAD can be found in the Real Property Information Model (RPIM Version 7.0). The RPAD follows the RPCS, and though each Service branch uses a slightly different classification scheme, each asset receives an RPAD current use facility analysis category code (FACCode) that is consistent with the RPCS system. See section 2.0 for discussion of RPCS classification and standard damage model information. The RPAD is For Official Use Only (FOUO) controlled.

Asset management systems and geographic information systems have traditionally been developed separately. For example, the NAVY iNFADS system and the Navy GeoReadiness system are only now becoming integrated. The RPAD is not a geo-referenced database, though the RPAD does include fields describing the site latitude and longitude, as well as length and width of assets.

Geo-referenced military asset data are available through the Homeland Infrastructure Foundation-Level Data (HIFLD) Homeland Security Infrastructure Program (HSIP) Gold dataset. The NGA assembles datasets, in partnership with the Department of Homeland Security and HIFLD, from a variety of Federal, State, and local agencies and commercial sources. NGA provides the HSIP Gold data as a unified homeland infrastructure geospatial data inventory and is a compilation of over 550 of the best available geospatial datasets, including military asset data provided from DISDI to NGA. HSIP Gold is controlled access, but available to federal employees and eligible contractors.[34]

HSIP Gold datasets on military assets that are relevant to impact and vulnerability assessment are shown in Table 12. These datasets may include standardized metadata and generally cover the United States, Puerto Rico, Guam, American Samoa, and miscellaneous islands. One advantage of the HSIP Gold data is that the military-relevant datasets are provided alongside a wide range of non-military datasets, including critical infrastructure, such as electric power generating plants, oil and natural gas pipelines, transmission lines, and levees. Additional information about building footprints may be available through public sources such as Google Earth or Open Street Map.

[34] https://www.hifldwg.org

Table 12. Military asset datasets available through HSIP GOLD.

Feature Class Name	Source	Feature Type	Record Count	Coverage
Defense_Site_Boundaries	Defense Installation Spatial Data Infrastructure (DISDI)	Area	2896	U.S., Puerto Rico, Guam, Northern Marianas, assorted islands & atolls
Defense_Site_Buildings	Defense_Site_ Buildings	Area	349619	U.S., Puerto Rico, Guam, Northern Marianas, assorted islands & atolls
Defense_Site_Locations	Defense Installation Spatial Data Infrastructure (DISDI)	Point	6632	U.S., Puerto Rico, US Virgin Islands, Guam, American Samoa, Northern Marianas, Misc. Islands
Defense_Site_Roads	Defense_Site_ Roads	Line	515256	U.S., Puerto Rico, US Virgin Islands, Guam, American Samoa, Northern Marianas, Misc. Islands
Military_Base_Boundaries	Navteq	Area	738	U.S., Can., Puerto Rico

Individual installations may have asset data records that are not included in the RPAD. We were unable to contact specific installation asset data managers within the scope of this study, but this is likely an important source to explore, especially for conducting detailed assessments where asset specific engineering drawings or CAD schematics are required. In addition, in applying the HAZUS model, asset data included in the model distribution may be appropriate for assessments that tolerate a high amount of uncertainty in the understanding of potential damages. In some specific locations, local governments may have city-specific data for off-base assets.

In this review, we analyze asset data quality based on the components identified in section 3.3, with additional attention to the completeness of records and alignment of the primary RPAD data source and the primary hazard model, HAZUS. We obtained RPAD data for the sample installations to better understand the data quality of available data for impact and vulnerability assessments. We focused on an initial subset of RPAD RPIM data elements (83 of 217), and upon initial review of the data, further refined our analysis to those data elements most relevant to impact and vulnerability assessment, especially in the application of the HAZUS model. The data elements include a unique identifier for each asset, the predominant use code (categorized after the RPCS hierarchy), the Plant Replacement Value, the Construction Material, Facility Built Date, Floors Above Ground, and the Facility Height.[35] We also

[35] Facility Height is defined in the RPIM v7.0: "The vertical distance measured from the approved ground floor elevation to the highest man-made part (antenna, weather vane, steeple, etc.) of the facility if it impacts mission

include Real Property Asset (RPA) Mission Dependency and Functional Capability to represent the critical nature of the asset and the state of function of the asset, respectively. We analyzed the completeness of these records across the sampled installations (see Table 13).

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operations. Use the roof as the highest point if the antenna, weather vane, steeple, etc. do not impact mission operations."

Table 13. Number of complete records for select data elements in asset installation site facility data

Name	Component	Total Records	Facility Plant Replacement Value	Construction Material	Facility Built Date	Floors Above Ground	Facility Height	RPA Mission Dependency**	Functional Capability##
Eglin Air Force Base	Air Force	55	4 (51 = $0)	55	55 (1908-2000)	55	55	55 (MC:55)	55 (F1=55)
Naval Station Norfolk	Navy	2549	2549 (6=$0)	2549 (2499 = "does not apply")	2549 (1824-2013)	2549	1822	2549 (MC:2547; NMD:2)	2549 (F1=1470; F2=335; F3=453; F4=291)
Naval Base Coronado	Navy	2632	2632	2632 (2626 = "does not apply")	2632 (1918-2013)	2632	1644	2632 (MC:2628; NMD:4)	2632 (F1=1127; F2=414; F3=765; F4=326)
Joint Base Elmendorf - Richardson	Air Force	2344	2344 (81=$0)	2344 (296 = "does not apply")	2344 (1940-2013)	2344	2344	2344 (MC:2343; NMD:1)	2344 (F1=1580; F2=577; F3=55; F4=134)
Naval Air Station Corpus Christi	Navy	824	824	824 (824 = "does not apply")	824 (1936-2013)	824	824	824 (MC:817; NMD:7)	824 (F1=522; F2=99; F3=120; F4=83)
Joint Base Lewis - McChord	Army	9229	9229 (142=$0)	9229 (1544 = "does not apply")	9229 (1934-2009)	9223	2601	7504 (MC: 6074; NMD:1428; MDNC:1)	8658 (F1=4360; F2=3732; F3=258; F4=308)
Joint Base Pearl Harbor - Hickam	Navy	8194	8194 (2=$0)	8194 (7221 = "does not apply")	8194 (1901-2013)	8194	6408	8194 (MC:8066; NMD:128)	8194 (F1=5857; F2=622; F3=1230; F4=485)
Naval Air Station in Sigonella, Italy	Navy	738	738 (3=$0)	738 (736 = "does not apply")	738 (1954-2013)	738	532	738 (MC:731; NMD:7)	738 (F1=523; F2=84; F3=92; F4=39)
Marine Corps Air Station Futenma	Marine Corps	6844	Not reviewed	6736 (5840 = "does not apply")	6844 (1937-2013)	6844	6844	6844 (MC:6744; NMD: 100)	6844 (F1=3724; F2=1958; F3=871; F4=291)

Codes for functionality of asset:

- F1: An asset that meets the function for which it is used with reasonable maintenance and without a need for a restoration and modernization project.
- F2: There will be a minimal requirement for restoration and modernization funds to make the asset capable of meeting the function for which it is used.
- F3: There will be a significant requirement for restoration and modernization funds to make the asset capable of meeting the function for which it is used.
- F4: The asset will require major restoration and modernization money to make it capable of meeting the function for which it is used.

**Codes for mission dependency:

- MC: Mission Critical
- NMD: Not Mission Dependent
- MDNC: Mission Dependent - Not Critical

The data quality for sampled installations varies widely. All assets are classified for a predominate use by the RPCS (not shown Table 13), an important step for considering applicability with HAZUS. Nearly all assets have a facility replacement value, which is also critical for assessing economic damages from impacts. However, although the construction material field is complete for nearly all assets, the choice of “does not apply” in most cases means that these values are generally not informative. In addition, the functional capability field is complete for nearly all records, with sites containing a mix of functioning assets and those that need some degree of restoration. At Naval Base Coronado, 1091 out of 2632 (41%) assets are listed as in need of ‘significant’ or ‘major’ restoration to make them capable of meeting intended use. This may help interpretation of impacts based on state or repair on the facility, but it is unclear how well standardized these data are across installations, which would be necessary for a Service-wide assessment. The records for Eglin Air Force Base appear problematic. Only 55 records are contained in the asset data, with all entered as mission critical and fully functional—dramatic differences from the other installations. It appears likely that data of lower functionality status were excluded.

It is clear that the RPAD covers a wide range of assets. Unfortunately, it is challenging to confirm the extent to which every installation asset is included, without ground-truthing or cross-referencing with other data sources. A similar issue exists for the HSIP Gold data from HFILD. In reviewing layers applicable to military installations, we found that no metadata exists for some HSIP Gold layers—at least it is not supplied with the standard distribution—and there are obvious gaps in asset information. Although RPAD and HSIP Gold represent the best available standardized data, great care is needed in application and interpretation to specific locations.

3.5 Findings and Recommendations

Although each assessment will differ in decision context, from our review, we identified several findings and recommendations related to data quality for the different levels of analysis proposed in section 1.2.

The data quality needs of an impact or vulnerability assessment will depend on the decisions that will be addressed. Aligning the information needed to the type of decision being made can reduce costs and help produce actionable results. The desired degree of confidence that a decision is correct dictates desired data quality. Therefore, decision makers should consider their tolerance for risk or uncertainty to guide the determination of whether data of sufficient quality are accessible.

In general, analysts and decision makers should keep in mind that for any given analysis that is supporting a decision, the ability to inform that decision will be limited by uncertainty across all datasets. This means that, for example, combing high accuracy topographic data with low accuracy asset elevational data does not improve the value beyond the low accuracy data. Finding consistency in data types within a particular analytical level will support efficient collection and use of data.

The time period of the decision to be informed may affect the requirements for data quality needs. For example, if one is looking out 100 years in an assessment and the historical record suggests that over the last 100 years changes due to natural coastal dynamics might be on the scale of many meters, sub-meter accuracy data will not reduce the uncertainty in the findings, even for a detailed assessment.

For asset data, the time since the last update to the building replacement value or facility physical quality will increase uncertainty. In addition, projecting impacts onto the current installation inventory over 100 years may introduce significant uncertainty due to the turnover in installation inventory, which can be as short as 20-30 years.

Data for reliable and defensible impact and vulnerability assessments, no matter the analytical level, must have metadata that adheres to accepted guidelines, the FGDC or ISO standards in particular. The incomplete metadata identified in this review may hinder the ability to conduct certain analyses. In addition, data used in analyses should be converted to consistent appropriate datums: NAVD88 and NAD83 for US installations. In general, the error introduced through datum conversion using modern techniques should not impact the quality of results for Service-level or installation-level screening analyses, but may influence results of a detailed assessment.

The spatial coverage and continuity requirements of the data will be related to the specific decision and tolerance for uncertainty; Service-level analyses will likely tolerate the uncertainty introduced by interpolation of data to un-sampled regions or combining different datasets, whereas detailed assessments will likely require consistently collected and continuous original topographic or bathymetric data. The limitations in an installation-level analysis will depend on the degree of discontinuity or lack of coverage.

For topographic and bathymetric data analyzed in this review, continuous data are generally available to support an installation-level analysis across coastal US locations; however, due to the non-uniform Lidar vertical error, additional review of local error may be needed to confirm reported values. Non-coastal locations and international installation sites have data coverage, but usually not at a vertical accuracy sufficient to support installation-level assessments.

The length or record for tidal stations is important for all levels of analysis and updates to local datums may be needed for detailed assessments at particular installations. The USACE recommends using a minimum tidal record length of 40 years (USACE, 2011). In situations where tidal records are shorter, the error introduced in interpolating from other stations will likely impact the ability to conduct a detailed assessment. Common techniques for dealing with shorter length of records should be sufficient for Service-level screening analysis, and for installation-level screening analysis the impact will vary. Bathymetric data collected by NOS hydrographic surveys, the primary bathymetric data source for U.S. installations, are required to report data adjusted to the MLLW vertical datum. This datum, and other tidal datums (i.e., Mean High Water), is the mean value from the current National Tidal Datum Epoch (1983-2001) (NOAA 2003b). However, local sea level rise due to vertical land movement and the influence of global sea level rise may change the tidal datum. In situations where there is low tolerance for uncertainty (i.e., detailed assessments), datum values may need to be updated with more recent observations to reflect current conditions.

In many coastal locations, recent topographic and bathymetric data will be needed, especially for installation-level screening or detailed assessments. The annual collection of data for the RPAD and annual updating of HSIP Gold data suggest that they are current enough for most analyses; nevertheless,

other concerns of completeness of data should not be overlooked. In locations where there is little subsidence or uplift, and where impacts from storms or human activities don't influence the elevation more than the level of accuracy needed in analysis, sufficient data exist for topographic and bathymetric data. Frequency of collection or last update to records of topographic, bathymetric and asset data varies at the locations sampled in this review.

The vertical error of a dataset has a large influence on delineating inundation zones (Zhang et al., 2011), especially in coastal areas with low topographic relief, as opposed to steep coastal relief. For Service-level screening, where comparability across global installations is needed, standard topographic data, such as Global 30 Arc-Second Elevation (GTOPO30) or SRTM sources may be appropriate. These data can be used to delineate the general outline of coastal zones. However, caution is needed in areas with low coastal relief, where error in vertical accuracy can have a dramatic influence on area of inundation (see Figure 9). Small and Nicholls (2003) and Ericson et al. (2006) used GTOPO30, a global 30 arc-second dataset to do study the global population at risk from coastal hazards. Because of their broad area coverage and improved resolution over GTOPO30, SRTM data have been used more recently in several studies of the land area and population potentially at risk from sea level rise (Dasgupta et al., 2007; McGranahan, Balk, and Anderson, 2007). In areas of low relief, the uncertainty in impacts or vulnerability that rely on these data will be high, however may be sufficient for identifying priorities across a military Service.

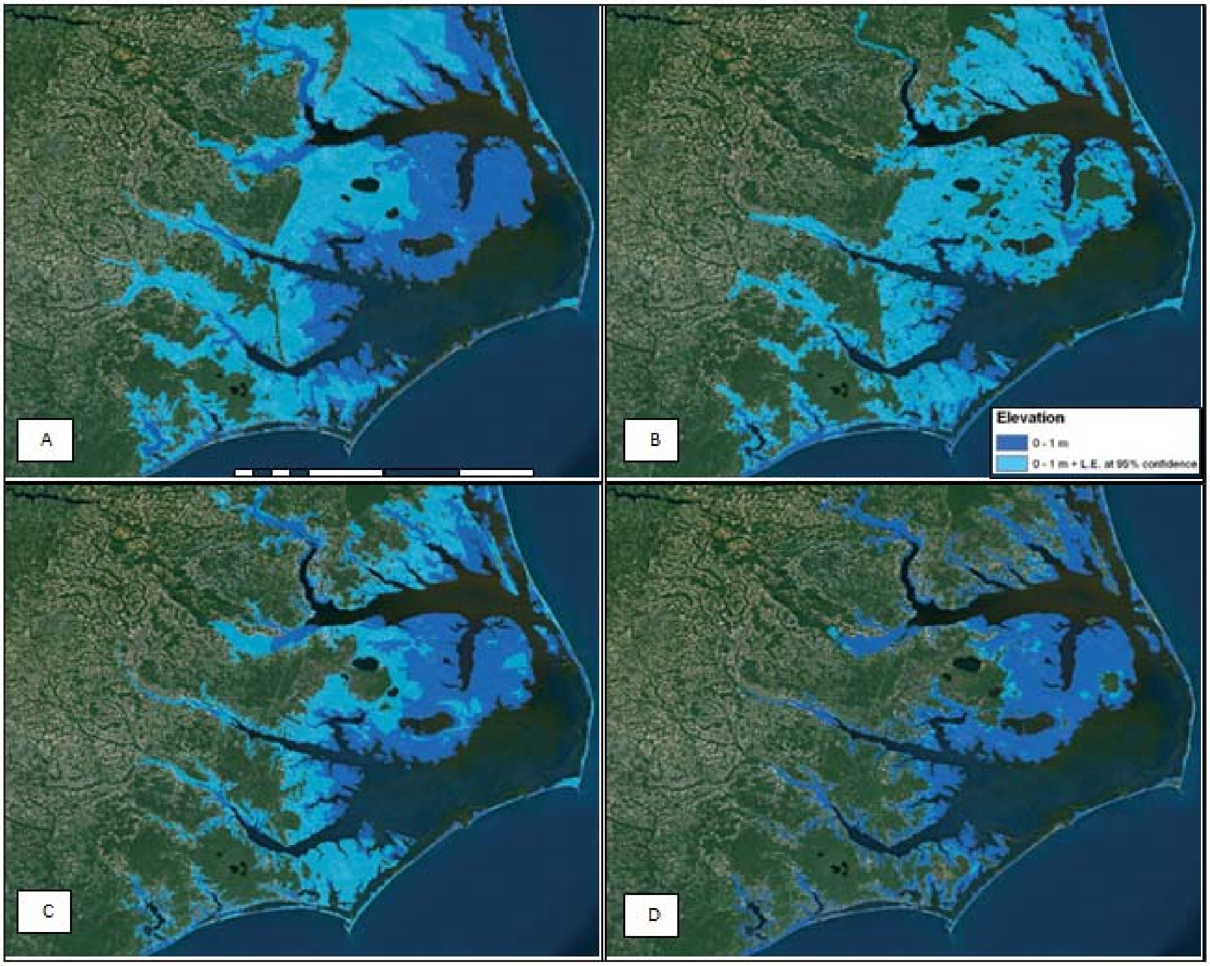

Figure 9. Maps of lands vulnerable to a 1 meter sea level rise, derived from (A) GTOPO30, (B) SRTM data, (C) 1 arc-second NED (USGS 30 meter DEM source), and (D) 1/9 arc-second NED (Lidar source). The background is a true color orthoimage. The darker blue shows potential inundation zones, and the lighter blue represents the area of uncertainty associated with the delineations (Gesch 2009).

Installation-level screening will normally require greater vertical accuracy and horizontal resolution in topographic and bathymetric data than for Service-level screening analyses. Lidar-derived data, usually provided with vertical accuracy of less than 15 cm, may provide sufficient information to support decisions from installation-screening level of analysis. Lidar elevation data have been successfully used for flood modeling in low relief areas (Bales et al., 2007; Sanders, 2007), and they can improve identification of coastal lands vulnerable to potential inundation from rising seas. The quality of Lidar data varies across datasets and caution should be used in situations where there is a low tolerance for uncertainty, but the data found in this review indicates that in many US coastal locations it may be sufficient for identifying priorities within an installation.

For detailed assessments, vertical accuracy of less than 10 cm will be needed to inform most decisions. Due to the many sources of error in Lidar data (see Box 3), Lidar-derived data are unlikely to be of sufficient quality. Real-time kinematic GPS data can provide topographic data at the level of accuracy desired, but the availability of such datasets is currently limited. In utilizing existing datasets of

this quality, user experience suggests that it will be necessary to check stated accuracy against local ground based measurements (Murdukhayeva et al., 2013), adding to the cost and time needed to reduce uncertainty to an appropriate level. For detailed impact and vulnerability assessments, where there is less tolerance for vertical error, asset elevational information must be precisely and consistently aligned to specific aspects of these assets and this must be reported in metadata. Our review indicates that such data are not commonly available through public sources for military installations.

The type and source of asset data needed for assessment will vary depending on level of assessment. Aggregate installation-level data available through DoD Base Structure Report and RPAD provide a globally consistent set of asset data that may be sufficient for Service-level screening analysis. Building footprint data available through HSIP Gold, in combination with RPAD data, may be sufficient for installation-level screening analyses. However, due to incomplete records of key asset elements in the RPAD database and HSIP Gold, those data may need to be supplemented with installation or Service-specific data sources. For detailed assessment, installation and asset specific engineering design specifications and CAD schematics will be necessary. Such data are not currently available through a central DoD source or other source.

4.0 Applicability of the HAZUS-MH Flood Model and/or Damage Information for Assessment of Impacts on Military Installations

DoD may consider using HAZUS-MH for flood vulnerability assessments under a changing climate, subject to the caveats noted in this report. As illustrated in Figure 10, HAZUS-MH can be driven by varying scales of user-provided information depending on time and resources. Based on the level of detail required, and degree of certainty provided by these analyses, we can roughly consider Level 1, below, to correspond to a department-wide or Service level screening, Level 2 to the larger installation level, and Level 3 to an installation or more detailed intra-installation level. The damage functions within HAZUS are not appropriate for detailed engineering design and construction.

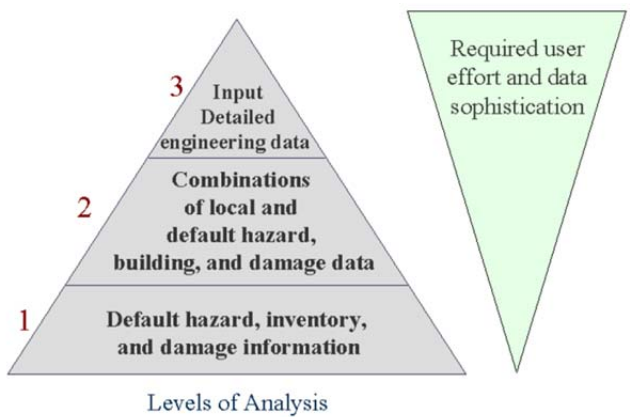

Figure 10. The level of analysis and user sophistication needed (FEMA, 2009).

Table 14 provides the strengths and weaknesses to DoD for running HAZUS-MH at each of three levels of analysis described in the HAZUS-MH model.

Table 14. The strengths and weaknesses for DoD to run HAZUS-MH at varying scales.

Level	Strengths	Weaknesses
Level 1	This level is not appropriate for DoD-wide analysis as assets at military installations need to be defined (HAZUS default inventory will not be sufficient)	
Level 2	Uniformity in approach Easily replicable and reproducible Transparent Based on accepted default damage information (some calibration may occur at this level)	Default information may not be well-calibrated to assets and require significant changes to depth-damage information Uncertainty associated with depth-damage information, etc.
Level 3	Installation specific assessment	Requires significant expertise and resources

The HAZUS-MH model has been widely applied within the United States to understand flood risks, and has also been applied internationally, though less widely. The model includes a library of damage curves for a range of assets, based on US data, but this library may not provide all asset coverage and quality

necessary for all applications at military installations, particularly ones requiring detailed, asset-specific analyses. The HAZUS-MH model relies predominantly on the depth-damage curves as described in Section 2.0. These curves are largely supplied by the Federal Insurance Mitigation Administration (FIMA), FIA, and various USACE District functions, and are widely considered as a standard of reasonableness (USACE, 2003). This collection of curves totals more than 900 damage functions (Scawthorn et al., 2006). Aside from the depth-related hazard loads, the damage functions include velocity-based building collapse curves (though tailored to Portland, Oregon) (USACE, 1985).

Although the HAZUS-MH flood model can be applied to military installations, it requires a high degree of HAZUS expertise to prepare and run the model (providing terrain information, constructing military asset database for use in HAZUS, and calibrating depth-damage curves as needed). Another option is to isolate and take out the asset-specific depth-damage information from the model and then combine this asset-specific depth-damage information with hydrologic/hydraulic modeling that provides changes in flood exposure (e.g., storm surge modeling of coastal inundation).

Throughout our interview process, some experts have cautioned that the HAZUS curves are often too general to be useful for a vulnerability assessment at a given military installation without calibration or further manipulation and development, though others suggest these curves represent the best of what is available and are acceptable for use. In practice, a few of our interviews recommended that if the HAZUS curves are used, that they be calibrated to the asset and context (however, this requires knowledge of the asset and past events, and other available information).

Another important consideration for DoD is the loss of asset functionality. Because estimating loss of functionality is not a primary purpose for the HAZUS-MH flood model, description of functionality impairment of assets is limited, as follows:

- Functionality of an essential facility such as a hospital will be lost (people evacuated) when flooding depth reaches 0.5 feet.
- Fragility curves suggesting loss of functionality for bridge types at a threshold of 25% of damage.
- Complete loss of functionality at specific water depth thresholds for utility assets (e.g., potable water systems, wastewater systems, petroleum systems, natural gas systems, and electric power systems).

This technique of a single depth-threshold for functionality may be too simplistic and generalized to meet DoD needs, particularly if DoD is interested in loss of levels of functionality for a given asset. Nevertheless, for critical assets where a loss of functionality may result in substantial impacts to the mission, these relationships should be further explored and developed based on asset depth-damage information provided by DoD stakeholders.

There are specific types of information required by asset to link the asset to the appropriate damage function. As noted previously, the damage functions embedded in HAZUS can be used in a stand-alone manner for asset-by-asset damage analysis. In addition, if DoD is using the HAZUS model for a flood analysis, the geographic location is needed to place the asset within the study region and corresponding level of flood inundation. Table 15 provides a description of the necessary information for identifying

damage functions by HAZUS categories and includes a cross-walk between HAZUS assets and the corresponding RPAD data elements relevant for impact or assessment modeling. In HAZUS, only the "General Building Stock" category has velocity-damage functions available, subsequent version of the model may provide this for the other categories.[36] Note the "replacement costs" and "repair costs" are not essential for mapping the asset to the appropriate damage-percent damage information but are necessary for estimating direct economic losses. The asset inventory for residential, commercial, government and other categories under general building stock is developed at the census block. This may not be relevant for a flood vulnerability assessment at a military installation where each asset is considered at a specific location. For use at a military installation, an added structure with a given geographic location could be mapped to large amount of available depth-percent damage information which is assigned to the general building stock.

[36] Personal communication, Eric Berman.

Table 15. Asset information required by asset type in HAZUS-MH and the associated damage information

Category	Asset information Required by HAZUS	Are there options for mapping the classification to depth-damage information?	RPAD Data Element	Methodology/ Results of Damage and Loss
General Building Stock	Classification by occupancy class Foundation type Assumed first floor elevation (typically pre-Firm and post-Firm) Presence of basement (required for cost estimates) Number of stories (required for cost estimates) Building Type (not important for flood but important for hurricane)	Yes, within an occupancy class there are choices generally based on foundation type and first floor elevation.	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value Facility height quantity Floor above ground quality Floor below ground quantity Construction Material Construction Type RPA Mission Dependency Functional Capability	The simulated depth of flooding is used to estimate the estimated percent damage from the depth-damage curves. The percent damage is then multiplied by the full (and depreciated) replacement value of the occupancy class in question to produce an estimate of total full (and depreciated) dollar loss. The damage states are derived from the percent damage (e.g., 1-10% damage is considered slight, 11-50% damage is considered moderate, 51-100% is considered substantial damage).

Category	Asset information Required by HAZUS	Are there options for mapping the classification to depth-damage information?	RPAD Data Element	Methodology/ Results of Damage and Loss
Transportation Systems	Geographic location Classification Replacement cost of system components	No	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value RPA Mission Dependency Functional Capability	Depth of flooding is compared to the height of critical components and the amount of damage can be estimated. In most cases, the elevation of the equipment provides for a depth of flooding at which point the functionality of the facility starts to become questionable. Tables are provided of percent of damage as function of water depth. Exception: Bridges; preliminary recommendation is that “failure” represents a damage value of 25% of damage.
Communication Systems	Geographic location Classification Replacement costs for facilities Repair costs for communication lines	No	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value RPA Mission Dependency Functional Capability	
Electric Power	Geographic location Classification Replacement costs for facilities Repair costs for transmission lines	No	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value RPA Mission Dependency Functional Capability	Tables are provided of percent of damage as function of water depth. Functionality threshold in terms of damage is also provided, as applicable.
Natural gas systems	Geographic location Classification Replacement costs for facilities Repair costs for pipelines	No	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value RPA Mission Dependency Functional Capability	

Category	Asset information Required by HAZUS	Are there options for mapping the classification to depth-damage information?	RPAD Data Element	Methodology/ Results of Damage and Loss
Oil systems	Geographic location Classification Replacement costs for facilities Repair costs for pipelines	No	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value RPA Mission Dependency Functional Capability	
Wastewater systems	Geographic location Classification Replacement costs for facilities Repair costs for pipelines	No	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value RPA Mission Dependency Functional Capability	
Potable water systems	Geographic location Classification Replacement costs for facilities Repair costs for pipelines	No	RPA Predominant Current Use CATCODE Code RPA Predominant Current Use FACCODE Plant Replacement Value RPA Mission Dependency Functional Capability	
High Potential Loss (HPL) facilities		No		User-specified

Assets not captured by flood damage information in HAZUS-MH include: sea walls, bulkheads, quay walls, small craft berthing, harbor protection facilities, moorings, marine improvements, artillery, pier, training support facilities and areas, ranges (e.g., small arms ranges, weapons ranges), cold storage, covered storage, open storage, underground administrative structures, outdoor facilities, heat and refrigeration, refuse and garbage facilities, non-potable water supply and distribution, sidewalks, and ground improvement structures. Note that HAZUS-MH does not yet fully assess the transportation and communication asset categories though the damage information is available (this is intended to be available at a later date).[37] In addition, the data elements provided in the RPAD data may not be complete or may vary from installation to installation, as shown in section 3.4.3. The utility of these data may be limited in HAZUS modeling, especially at level 2 or level 3 HAZUS analyses.

Overall, the HAZUS model provides flood damage information accepted by USACE and FEMA for a large number of assets located at military installations that, in theory, can be used consistently across military bases in the United States. Beyond national boundaries, additional analysis may be required. One interviewee suggested that the current damage information in HAZUS may be appropriate as the U.S. bases in foreign lands will generally be designed similarly as those domestically (i.e., assets will be similar); however, the climate data (e.g., flooding depth and duration, and/or time series of rainfall, runoff, and other parameters to support hydrologic modeling, if needed) may not exist to inform the hazard load exposure. In terms of damage metric, although the majority of the damage functions focus on economic losses, functionality of some assets (for given flood depths) has been included in some of the damage state information that may be useful for DoD purposes in determining whether the mission is operational. Moving forward, DoD may consider this model as the best widely available one for their purposes in estimating flood damage for a first-order analysis of a Level 2 assessment (as defined by HAZUS).

[37] Personal Communications, Eric Berman

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6.0 Appendices

Appendix A: List of Persons Interviewed

The authors conducted a series of interviews to complement the literature reviewed. Interviews included SERDP study PIs, key individuals identified by SERDP, and individuals identified as experts through an initial set of interviews. The interviews were semi-structured, with a general set of questions designed to elicit expertise on types of models, fragility and damage information, and data used in impact or vulnerability assessments, sources of these data, the quality of available data, data gaps, and strategies to address relevant gaps (see list of questions below). From the general set of questions, additional questions were tailored to take advantage broad range of backgrounds and knowledge of the experts represented. A table of interviewees is provided herein.

Table 16. List of persons interviewed (including those contacted but not interviewed) in conjunction with this study.

Name	Organization	Interviewed? (Y/N)
Jeroen Aerts and Brenden Jongman	Institute for Environmental Studies	Y
Eric Berman	HAZUS Program Manager	Y
David Kreibel	US Naval Academy	Y
Angela Schedel	US Naval Academy, University of Maryland PhD candidate	Y
Kelly A. Burks-Copes	USACE/University of Florida	Y
Martin T. Schultz	USACE, Environmental Engineer	Y
Marianne W. Petty	Office of the Deputy Under Secretary of Defense	Y
Jose Rullan-Rodriguez	USACE, Research Civil Engineer (Structural)	Y
Michael Case	USACE, Engineer Research and Development Center	Y
John Marra	NOAA National Climatic Data Center	Y
Curt Storlazzi	U.S. Geological Survey	Y
Jeffrey Donnelly	Woods Hole Oceanographic Institution	Y
Richard Moss	Battelle, Pacific Northwest Division	Y
Joseph Donoghue, Steve Kish, Jim Elsner (group interview)	Oklahoma State University, Florida State University	Y
Robert Evans	Woods Hole Oceanographic Institution	Y
David LaBranche	DISDI Program Manager, OSD Defense Installations Spatial Data Infrastructure Office	Y
Justin LaRose	DISDI Program Manager, OSD Defense Installations Spatial Data Infrastructure Office	Y
Adam Parris	NOAA Regional Integrated Sciences and Assessments Program	Y
Chris Weaver	U.S. Global Change Research Program	Y

Name	Organization	Interviewed? (Y/N)
Shawn Lewers	Florida State University	Y
Robin O'Connell	Naval Facilities Engineering Command	Y
Kate White	USACE, Institute for Water Resources	N
Ann Kosmal	General Services Administration	N
Jake Keller	Parsons Brinckerhoff	N
Bob Carl	USACE, , Institute for Water Resources, Hydrologic Engineering Center	N
Keith Autry	Office of the Assistant Secretary of the Navy for Installations, Energy and Environment	N
Kevin Knuuti	US Army Engineer Research and Development Center	N
Rachel Ann Davidson	University of Delaware	N

Key Questions for Interviewees

1. Are there certain standards that need to be met or sources of data that are required for the data to be used in decision making? (e.g., do certain types of asset/bathy/topo data need to arise from a particular source/agency?)
2. To what extent do the Services and installations collect data consistent with the real property typology?
    a. To what extent are data that are collected in-house comparable across installations?
    b. Are there uncommon/idiosyncratic data types that we should consider (e.g., impervious surfaces)? Are changes over time monitored?
3. What information/data is appropriate for a Service-wide screening? For an installation-wide screening? For a detailed assessment? Have you encountered difficulties in obtaining quality, sufficient resolution data in your assessments
4. Are you using bathymetry and topographic data from the USGS (10m or 3m) in decision making? How are you considering the vertical error associated with these data sources?
USGS Map Viewer for US, showing 10m/3m topography coverage:
http://viewer.nationalmap.gov/viewer/
5. Do you use specific techniques for transforming data layers across different vertical datums (such as through NOAA's VDatum tool)? If so, how do you characterize any errors associated with the technique?
6. Do you use specific techniques for integrating various topographic/bathymetric data layers with varying degrees of horizontal and vertical resolution?
    a. If you have integrated these datasets and created a surface (TIN) for modeling (i.e. storm surge modeling), what is the level of uncertainty associated with this interpolated surface?

7. Have you been able to characterize error or uncertainty across the analysis, for example from initial elevational data for area through cascading modeling steps?
8. What kind of damage/fragility models are run right now for operational and planning decision making?
9. We have proposed to briefly discuss the implications of the report's findings for a few illustrative decisions. What would be good examples particularly at the detailed assessment level? (E.g., renovating shoreline structure? upgrading storm drainage? expanding energy generating facilities?)
10. Who are some of the other critical people / groups we should interview?

For people who are expert in damage modeling…

11. We are considering the use of this (i.e. the model the interviewee is expert on) model for military installations, do you have any thoughts on how well this model would suit this purpose?
    a. What about HAZUS on military installations?
    b. If experienced with HAZUS, how seamless does the real property database fit within the HAZUS format for information? How much manipulation of the information is required? What information is missing?
12. Can you comment on the strengths and weaknesses of the model- and how well the model addresses uncertainty?
    a. In particular, how well the damage/fragility curves *capture direct and indirect damages*?
13. We are looking across models to select or recommend models for this purpose, in your work have you considered model selection criteria that are particularly useful?
14. Compared to like models, do you consider this model particularly challenging to learn and adapt for particular purposes?
15. Are there other models you would recommend we consider? (Are there models appropriate for specific scales of analysis, like each asset on an installation versus across the entire mid-Atlantic?)
16. How applicable is your model in data sparse regions of the world?
17. When was the latest release? Is the model undergoing any revisions that affect the damage/fragility curves?

Appendix B: A Crosswalk of RPAD Asset Coverage for the HAZUS-MH Flood Model

This table presents a crosswalk of asset coverage in the HAZUS-MH Flood model damage functions against the Real Property Database Tier IV Asset Class.

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
Class 1: Operation and Training				
11 Airfield pavements		• 111 Airport runway: Airport runways (APTR)		• *112 Airfield taxiways* • *113 Airfield aprons* • *116 Other airfield pavements*
12 Liquid Fueling and Dispensing Facilities	• 124 Operating fuel storage facilities: Oil / Natural gas exposed transmission Pipelines River Crossing (O1PE/NGPE), Oil / Natural gas Buried transmission pipelines river crossings (O1PB / NGPB), Oil / Natural gas Pipelines (non-crossing) (O1P / NGP)	• 121 Aircraft fuel dispensing facilities: Air Fuel Facilities (AFF) • 122 Marine fuel dispensing facilities: Port fuel facility (PFF) • 123 Land vehicle fuel dispensing facilities: Railway fuel facility (RFF), Bus fuel facility (BFF)		
13 Communications, Navigation Aids and Airfield Light		• 131 Communications Buildings: Communication System Central Offices/Switching stations below grade and at/above grade (CCS1, CCS2), Other communication facility (CBO), Radio/TV station (CBR), Weather station (CBW), Railway dispatch facility (RDF), Bus dispatch facility (BDF) • 133 Aviation Navigation and Traffic Aids Buildings: Wood / steel / concrete / brick airport control towers (ACTW,ACTS, ACTC, ACTB), Heliport facilities (AFH) • 135 Communication Lines: Exposed Communications Lines River Crossings (CCTE), Buried Communications Lines River Crossings (CCTB), Communications Lines (non-crossings) • 137 Ship Navigation and Traffic Aids Buildings: Ferry dispatch facility (FDF)		• *132 Communications Facilities Other than Buildings* • *134 Aviation Navigation and Traffic Aids Facilities Other than Buildings* • *136 Airfield Pavement Lighting* • *138 Ship Navigation and Traffic Aids Other than Buildings*

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
14 Land Operational Facilities		• 140 Ground Operational Buildings : Steel / concrete / wood / brick railway urban station (RSTS / RSTC / RSTW / RSTB) , Steel / concrete / wood / brick railway maintenance facility (RMFS, RMFC, RMFW, RMFB), Steel / Concrete / Brick / Wood urban bus station (BPTS, BPTC, BPTB, BPTW) • 141 Airfield Operational Buildings : Wood / steel / concrete / brick airport control towers (ACTW,ACTS, ACTC, ACTB), Heliport facilities (AFH) • 142 Helium Plants and Storage: Port Fuel Facility (PFF) • 143 Ship Operational Buildings : Waterfront Structures • 144 Operational Support Buildings : Steel / Concrete / Brick / Wood maintenance facility (BMFW, BMFS, BMFC, BMFB) • 148 Ship Operational Facilities Other than Buildings : Ferry dispatch facility (FDF)		• *145 Ground Operational Facilities Other than Buildings* • *146 Airfield Operational Facilities Other than Buildings*
15 Waterfront Operational Facilities		• 151 Piers and Wharfs : Waterfront structures (PWS1) • 153 Cargo Handling and Storage Areas : Cranes/cargo handling equipment (PEQ), Wood / steel / concrete / brick warehouses (PWHW / PWHC / PWHB / PWHB)		• *154 Sea Walls, Bulkheads, and Quay Walls* • *155 Small Craft Berthing*
16 Harbor and Coastal Operational Facilities				• *161 Harbor Protection Facilities* • *163 Moorings* • *164 Marine Improvements*
17 Training Facilities	• 171 Training Buildings : Government general services buildings (GOV1), Business/Professional/ Technical Services (COM4) • 172 Simulation Facilities: Government general services buildings (GOV1)			• *173 Training Support Facilities* • *174 Impact, Maneuver, and Training Areas* • *175 Small Arms Ranges* • *176 Weapons Ranges* • *177 Team and Unit Ranges* • *178 Explosives and Flame Ranges* • *179 Training Facilities Other Than Buildings*

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
Class 1: Maintenance and Production[38]				
21 Maintenance Facilities	• 212 Guided Missile Maintenance Facilities : Government general services buildings (GOV1)* • 213 Ships and Spares Maintenance Facilities: Government general services buildings (GOV1)* • 214 Tank and Automotive Maintenance Facilities: Government general services buildings (GOV1)* • 215 Weapons and Spares Maintenance Facilities : Government general services buildings (GOV1)* • 217 Electronics and Communications Equipment Maintenance Facilities : Government general services buildings (GOV1)* • 218 Miscellaneous Items and Equipment Maintenance Facilities : Government general services buildings (GOV1)* • 219 Installation Repair and Operation Maintenance Facilities : Government general services buildings (GOV1)*	• 211 Aircraft Maintenance Facilities : Wood / Steel / Concrete / Brick Airport Maintenance & Hanger Facility (AMFW / AMFS / AMFC / AMFB)	• 216 Ammunition, Explosives, and Toxics Maintenance Facilities : Military arsenals (HPMI11)	

[38] In addition, HAZUS can provide induced damage from hazardous material release.

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
22 Production Facilities	The following depth-damage data in HAZUS may provide a match: ▪ Heavy / light industrial facilities (IND1 / IND2)*, ▪ Food drug and chemical industrial facilities (IND3)*, ▪ Metals and mineral processing facilities (IND4)*, ▪ High technology facilities (IND5)*, Construction facilities (IND6)* with the following RPD categories: • 221 Aircraft Production Facilities • 222 Guided Missile Production Facilities • 223 Ships and Spares Production Facilities • 224 Tank and Automotive Production Facilities • 225 Weapons and Spares Production Facilities • 226 Ammunition, Explosives, and Toxics Production Facilities • 227 Electronics and Communications Equipment Production Facilities • 228 Miscellaneous Items and Equipment Production Facilities • 229 Installation Maintenance and Repair Production Facilities			
Class 1: Research, Development, Test, and Evaluation				
31 RDT&E Buildings	The following depth-damage data in HAZUS may provide a match: ▪ Government general services buildings (GOV1)*, ▪ Heavy / light industrial facilities (IND1 / IND2)*, ▪ Food drug and chemical industrial facilities (IND3)*, ▪ Metals and mineral processing facilities (IND4)*, ▪ High technology facilities (IND5)*, Construction facilities (IND6)* with the following RPD categories: • 310 Research, Development, Test and Evaluation Science Laboratories			

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
	• 311 Aircraft Research, Development, Test and Evaluation Buildings • 312 Missile and Space Research, Development, Test and Evaluation • 313 Ship and Marine Research, Development, Test and Evaluation Buildings • 314 Tank and Automotive Research, Development, Test and Evaluation Buildings • 315 Weapons and Weapon Systems Research, Development, Test and Evaluation Buildings • 316 Ammunition, Explosives, and Toxics Research, Development, Test and Evaluation Buildings • 317 Electronic and Communication Equipment Research, Development, Test and Evaluation Buildings • 318 Propulsion Research, Development, Test and Evaluation Buildings • 319 Miscellaneous Items and Equipment Research, Development, Test and Evaluation Buildings • 320 Underwater Equipment Research, Development, Test and Evaluation Buildings • 321 Technical Services Research, Development, Test and Evaluation Buildings			
37 RDT&E Range Facilities	• 371 Research, Development, Test and Evaluation Range Facilities : Military administrative offices (HPMI5)		• 371 Research, Development, Test and Evaluation Range Facilities : Military administrative offices (HPMI5)	
39 RDT&E Facilities Other Than Buildings				• *390 Research, Development, Test and Evaluation Range Facilities Other than Buildings*
Class 1: Supply				
41 Liquid Storage - Fuel and Nonpropellants	• 412 Liquid Storage Other than Water, Fuel, and Propellants : Chemical industrial facilities (IND3)*	• 411 Bulk Liquid Fuel Storage : Port Fuel Facility (PFF), Bus Fuel Facilities (tanks) (BFF), Ferry Fuel Facility (FFF), Airport Fuel Facility (AFF), Oil Tank Farm (OTF), Railway Fuel Facility (RFF)		

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
42 Ammunition Storage			• 421 Depot and Arsenal Ammunition Storage : Military arsenals (HPMI11) • 422 Installation and Ready Issue Ammunition Storage : Military arsenals (HPMI11) • 423 Liquid Propellant Ammunition Storage : Military arsenals (HPMI11) • 424 Weapon-Related Battery Storage : Military arsenals (HPMI11) • 425 Open Ammunition Storage : • Military arsenals (HPMI11)	
43 Cold Storage				• *431 Depot and In-Transit Cold Storage* • *432 Installation and Ready Issue Ammunition Storage*
44 Covered Storage				• *441 Depot and Arsenal Covered Storage* • *442 Installation and Organization Covered Storage*
45 Open Storage				• *451 Depot Open Storage* • *452 Installation and Organization Open Storage*
Class 1: Hospital and Medical				
51 Medical Centers and Hospitals	• 510 Medical Centers and Hospitals : Hospital (COM6)*, Small / Medium / Large Hospital (EFHS / EFHM / EFHL)			
53 Medical and Medical Support Facilities	• 530 Medical and Medical Support Facilities : Medical Office/clinic (COM7)*, Medical clinics (EFMC)			
54 Dental Clinics	• 540 Dental Clinics : Medical Office/clinic (COM7)*, Medical clinics (EFMC)			
55 Dispensaries and Clinics	• 550 Dispensaries and Clinics : Medical Office/clinic (COM7)*, Medical clinics (EFMC)			
Class 1: Administrative				
61 Administrative Buildings	• 610 Administration Buildings : Government general services (GOV1)*, Military administrative offices (HPMI5)			

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
62 Underground Administrative Structures				• *620 Underground Administrative Structures*
69 Administrative Structures Other Than Buildings				• *690 Administrative Structures Other Than Buildings*
Class 1: Housing and Community				
71 Family Housing	• 711 Family Housing Dwellings[39] : Single Family Dwelling (RES1)*, Multi Family Dwelling - Duplex / 3 to 4 units / 5 to 9 units / 10 - 19 units / 20-49 units / 50+ units (RES3A, RES3B, RES3C, RES3D, RES3E, RES3F)* • 712 Family Housing Trailers : Mobile home (RES2)*, Temporary lodging (RES4)* • 714 Detached Family Housing Facilities : Single Family Dwelling (RES1)*, Multi Family Dwelling - Duplex / 3 to 4 units / 5 to 9 units / 10 - 19 units / 20-49 units / 50+ units (RES3A, RES3B, RES3C, RES3D, RES3E, RES3F)*			• *713 Family Housing Trailer Sites*
72 Unaccompanied Personnel Housing	• 721 Enlisted Unaccompanied Personnel Housing : Institutional dormitory (RES5)*, Military barracks/group quarters (HPMI1), Military officer/enlisted quarters -multi unit (HPMI2)		• 721 Enlisted Unaccompanied Personnel Housing : Military barracks/group quarters (HPMI1), Military officer/enlisted quarters -multi unit (HPMI2) • 722 Unaccompanied Personnel Housing Mess Facilities : Mess Halls (HPMI6) • 723 Detached Unaccompanied	• *725 Emergency Unaccompanied Personnel Housing Facilities*

[39] Damage to flood is estimated in percent and is weighted by the area of inundation at a given depth for a given census block. Depth of flooding (feet) is measured from the top of the first finished floor and damage is provided as % of damage and replacement cost. The 6 FIMA (FIA) residential depth-damage curves available are a function of occupancy class. The entire composition of each type of relevant general building stock within a given census block is assumed to be evenly distributed throughout the block and allows for 33 occupancy classifications and 5 general construction classifications. Building age is a key parameter for estimating expected flood damage (age is an issue because building codes (and expected building performance) change over time, and because development regulations change when a community enters the National Flood Insurance Program (NFIP)). The ranges are in decades starting with pre-1939 structures and including every decade up to 1990. The FIA1 "credibility weighted" depth-damage curves based on basis of 20 years of empirical damage data, and selected curves developed by the U.S. Army Corps of Engineers (USACE), and the USACE Institute for Water Resources (USACE IWR). *Functions have also been compiled specific for the USACE Chicago, Galveston, New Orleans, New York, Philadelphia, St. Paul, and Wilmington Districts.* [HAZUS Technical Manual]

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
			Personnel Housing Facilities : Military officer/enlisted quarters - detached (HPMI3) • 724 Officer Unaccompanied Personnel Housing Facilities : Military officer/enlisted quarters -multi unit (HPMI2), Military officer/enlisted quarters - detached (HPMI3)	
73 Personnel Support and Services Facilities	• 731 Safety, Discipline, and Rehabilitation Facilities : Government general services (GOV1)* • 732 Installation Support Facilities : Government general services (GOV1)*, • 734 Retail Sales and Service Facilities : Retail Trade (COM1)*, Wholesale Trade (COM2)*, Personal and Repair Services (COM3)*, Business/Professional/Technical Services (COM4)* • 735 Education Facilities : Default school (SDFLT), School (EFS1) • 736 Religious Facilities : Church/ Membership Organizations (REL1)		• 731 Safety, Discipline, and Rehabilitation Facilities Military administrative offices (HPMI5) • 732 Installation Support Facilities : Military administrative offices (HPMI5) • 733 Food Service Facilities : Mess Halls (HPMI6) •	• *737 Family and Child Support Facilities* • *738 Miscellaneous Personnel Support and Services Facility*
74 Indoor Morale, Welfare, and Recreation Facilities	• 741 Indoor Recreation Facilities : Entertainment and recreation (COM8)* • 743 Indoor Entertainment Facilities : Entertainment and recreation (COM8)*, Theaters (COM9*) • 744 Miscellaneous Indoor Morale, Welfare and Recreational Facilities : Entertainment and recreation (COM8)*		• 741 Indoor Recreation Facilities :, Military gymnasiums/armory (HPMI8) • 742 Indoor Athletic Facilities : Military gymnasiums/armory (HPMI8) • 743 Indoor Entertainment Facilities : Military officer/enlisted clubs (HPMI7)	
75 Outdoor Morale, Welfare, and Recreation Facilities				• *751 Outdoor Recreation Facilities* • *752 Outdoor Athletic Facilities* • *753 Outdoor Entertainment Facilities* • *754 Miscellaneous Outdoor Morale, Welfare and Recreational Facilities*
76 Museums And Memorials				• *760 Museums and Memorials*

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
Class 1: Utility & Ground Improvements[40,41]				
81 Electrical Power	• 811 Electric Power Source : Small / medium / large electric power plants (EPPS, EPPM, EPPL) • 812 Electric Power Transmission and Distribution Lines : Electric power distribution circuits elevated crossings / buried crossings / non-crossing (EDCE / EDCB / EDC) • 813 Electric Power Substations and Switching Stations : Electric power system low / medium / high voltage substation (ESSL, ESSM, ESSH)			
82 Heat and Refrigeration (Air Conditioning)				• *821 Heat Source* • *822 Heat Transmission and Distribution Lines* • *823 Heat Gas Source* • *824 Heat Gas Transmission* • *826 Refrigeration (Air Conditioning) Source* • *827 Chilled Water (Air Conditioning) Transmission and Distribution Lines*

[40]Depth-damage is similar to that of general building stock with the elevation of the equipment also provides for a depth of flooding at which point the functionality of the facility starts to become questionable - these curves are defined by "Flood Model project team" that developed HAZUS-MH; in addition, curves accounting for inundation (function of water elevation) and debris impact/hydrologic loading (function of water elevation/velocity) are also available

[41] Transportation: depth-damage is similar to that of general building stock with the elevation of the equipment, also provides for a depth of flooding at which point the functionality of the facility starts to become questionable - these curves are defined by "Flood Model project team" that developed HAZUS-MH; in addition, curves accounting for inundation (function of water elevation) and debris impact/hydrologic loading (function of water elevation/velocity) are also available

Bridges: bridge scour (function of velocity/duration); Velocity-based building collapse curves developed by the Portland District of the U.S. Army Corps of Engineers (IWR 85-R-5, 1985): collapse potential (e.g., collapse or no collapse) to overbank velocity (in feet per second) and water depth (in feet) for three building material classes (wood frame, steel frame, and masonry or concrete bearing wall structures). Note: assumed that below velocities of 2 feet per second, collapse potential is extremely low and damage is due to inundation only.

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
83 Sewage and Waste	• 831 Sewage and Industrial Waste Treatment and Disposal : Small / medium / large wastewater treatment plants (WWTS, WWTM, WWTL), Wastewater system exposed / buried collector river crossings (WWPE, WWPB), Waste water control vaults and control stations (WWCV), Small lift stations wet well and dry well / submersible (WLSW, WLSS), Med and large lift stations wet well and dry well / submersible (WLMW, WLMS) • 832 Sewage and Industrial Waste Collection Lines : Pipes (non-crossings) (WWP)			• *833 Refuse and Garbage Facilities*
84 Water	• 841 Potable Water Supply, Treatment and Storage : Small / medium / large treatment plants open/gravity (PWSO, PWMO, PWLO), Small / medium / large water treatment plants closed/pressure (PWSC, PWMC, PWLC), Control vaults and stations (PCVS), Water storage tanks at grade concrete / steel / wood (PSTC, PSTS, PSTW), Water storage tanks elevated (PSTE), Water storage tanks below grade (all) (PSTB), Wells (PWE) • 842 Potable Water Distribution System : Exposed / buried potable water transmission pipeline crossing (PWPE, PWPB), Potable water pipelines (crossing) (PWP), Small / med and large pumping plants below grade (PPSB, PPMB), Small / med and large pumping plants above grade (PPSA, PPMA) • 843 Fire Protection Water Facilities : Default fire station (FDFLT), Fire station (EFFS)			• *844 Nonpotable Water Supply and Storage* • *845 Nonpotable Water Distribution Facilities*
85 Roads and Other Pavements		• 851 Road : Major (1 km 4 lanes) / urban (1 km 2 lane) highway roads (HRD1 / HRD2) •		• *852 Sidewalks and Other Pavements*

Class 2 Asset Category	Available in HAZUS	Pending (damage information available in HAZUS technical manual but incorporated yet into live version)	Asset information in HAZUS but user most provide damage curves/ data	Not Available
86 Railroad Facilities		• 860 Railroad Tracks : Railway tracks (RTR) • 861 Railroad Facilities Other than Tracks : Railway bridge unknown / concrete / steel / wood (RBRU, RBRC, RBRS, RBRW), Railway tunnel (RTU)		
87 Ground Improvement Structures				• *871 Grounds Drainage* • *872 Grounds Fencing, Gates, and Guard Towers*
89 Miscellaneous Utilities				• *891 Miscellaneous Utilities – Square Feet* • *892 Miscellaneous Utilities – Each* • *893 Miscellaneous Utilities – Linear Feet* • *895 Miscellaneous Utilities – Gallons* • *899 Miscellaneous Components of Other Facilities*
Class 1: Land				
91 Land				• *911 Land Purchase, Condemnation, Donation, or Transfer* • *912 Public Domain Withdraw* • *913 License and Permit* • *914 Public Land of Territories and Possessions*
92 Other Rights				• *922 In-Lease* • *923 Foreign Right*
93 Improvements to Facilities or Sites				• *931 Building Improvements* • *932 Clearing, Grading and Landscaping* • *933 Demolition of Facilities* • *935 Dredging* • *939 Other Improvements*
94 Contaminated Land				• *940 Contaminated Facility or Area*

Appendix C: Model Criteria for Cataloguing the Models

The objective of the model review is to identify the strengths and weaknesses of the models, including the gaps in hazard and infrastructure coverage related to DoD infrastructure. To that end, a model catalogue was been developed in Microsoft Excel to organize the information and ensure that it is easily accessible. The following outlines a set of criteria used to catalogue the models, providing a basis for inter-comparison, and better enabling users to identify models that may fulfill their needs:

- Contact: Those individual experts we have identified who we may interview about a particular model
- Model: Name of the model
- Owner: Organization or entity that developed or owns the model
- Model Objective: Purpose of the model.
- Climate Stressor Type(s): Type of climate stressor or stressors required as input to the model
- Climate Stressor Metric(s): Outlines how the magnitude of the climate stressor is assessed, including the required inputs or models used to assess magnitude (i.e., depth of flooding)
- Categories of Infrastructure Assessed: Basic categories of infrastructure addressed (e.g., buildings, transportation)
- Geographic Area: Applicability of the model to different geographies or places
- Damage Assessment: Outlines how damage is assessed, for example, by identifying what is on the axis of the fragility curves, e.g. depth of flooding and economic damage
- Details on Damage Assessment by DoD Facility Class
    - Operation and Training
    - Maintenance and Production
    - R&D, Test, and Evaluation
    - Supply
    - Hospital and Medical
    - Administrative
    - Housing and Community
    - Utility & Ground Improvements Land
- Indirect Impacts Assessed: Considers whether indirect impacts (e.g., electrical service interruption causes a failure in water supply) or cascading impacts (e.g., business interruption as a bridge is no longer functional) are considered
- Uncertainty Treatment: How model uncertainty is treated
- Other Environmental Data Needs: Particular focus on data types being covered in Task 2 (bathymetry)
- Non-environmental Data Needs: Requirements specific to the assets and their valuation
- Additional Information: Software requirements, website / citation, information sources (reports, interviews, articles), other-like models

Appendix D: DoD Real Property Classification System (RPCS)

The RPCS is a hierarchical scheme of real property types and functions that serves as the framework for identifying, categorizing, and analyzing the department's inventory of land and facilities around the world. This scheme is comprised of a 5-tier structure represented by numerical codes, with 1-digit codes being the most general and 5- or 6-digit codes representing the most specific types of facilities[42]. Our analysis focus on the first and second tiers (see Table 1), and may include the third tier of classification for more common infrastructure types included in fragility and damage models.

Table 1. DoD Facility Classes. Note that the RPCS structure is numerically consistent between the 1-digit level and the 4-digit level. For example, the Facility Class represented by the code "1" for "Operation and Training facilities" includes all of the asset types described by the 2-, 3-, and 4-digit codes that also begin with the numeral 1. Likewise, the Category Group represented by the code "11" for "Airfield Pavements" consists of the 3- and 4- digit codes that also begin with "11."

DoD Facility Class (1 digit)	DoD Category Group (2 digit)
1 Operation & Training	
	11 Airfield Pavements
	12 Liquid Fueling and Dispensing Facilities
	13 Communications, Navigation Aids and Airfield Light
	14 Land Operational Facilities
	15 Waterfront Operational Facilities
	16 Harbor and Coastal Operational Facilities
	17 Training Facilities
2 Maintenance & Production	
	21 Maintenance Facilities
	22 Production Facilities
3 Research, Development, Test, and Evaluation	
	31 RDT&E Buildings
	37 RDT&E Range Facilities
	39 RDT&E Facilities Other Than Buildings
4 Supply	
	41 Liquid Storage - Fuel and Nonpropellants
	42 Ammunition Storage
	43 Cold Storage
	44 Covered Storage
	45 Open Storage
5 Hospital & Medical	
	51 Medical Centers and Hospitals
	53 Medical and Medical Support Facilities

[42] Please refer to http://www.dtic.mil/whs/directives/corres/pdf/416503p.pdf

DoD Facility Class (1 digit)	DoD Category Group (2 digit)
	54 Dental Clinics
	55 Dispensaries and Clinics
6 Administrative	
	61 Administrative Buildings
	62 Underground Administrative Structures
	69 Administrative Structures Other Than Buildings
7 Housing & Community	
	71 Family Housing
	72 Unaccompanied Personnel Housing
	73 Personnel Support and Services Facilities
	74 Indoor Morale, Welfare, and Recreation Facilities
	75 Outdoor Morale, Welfare, and Recreation Facilities
	76 Museums And Memorials
8 Utility & Ground Improvements	
	81 Electrical Power
	82 Heat and Refrigeration (Air Conditioning)
	83 Sewage and Waste
	84 Water
	85 Roads and Other Pavements
	86 Railroad Facilities
	87 Ground Improvement Structures
	89 Miscellaneous Utilities
9 Land	
	91 Land
	92 Other Rights
	93 Improvements to Facilities or Sites
	94 Contaminated Land